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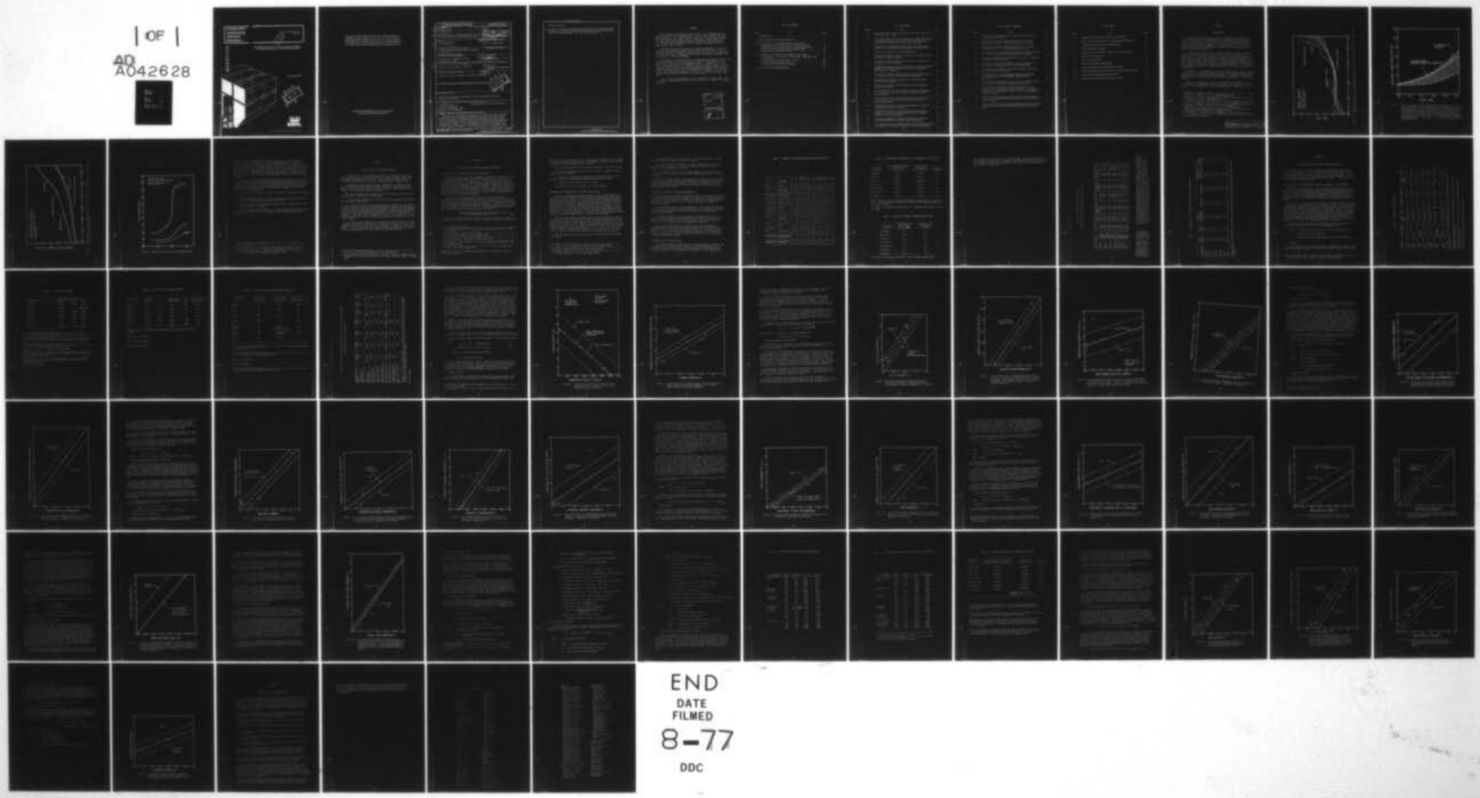

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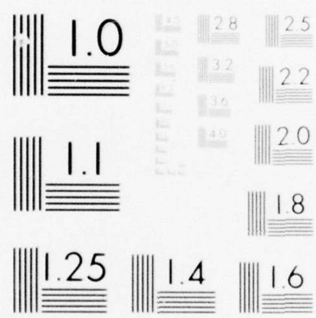

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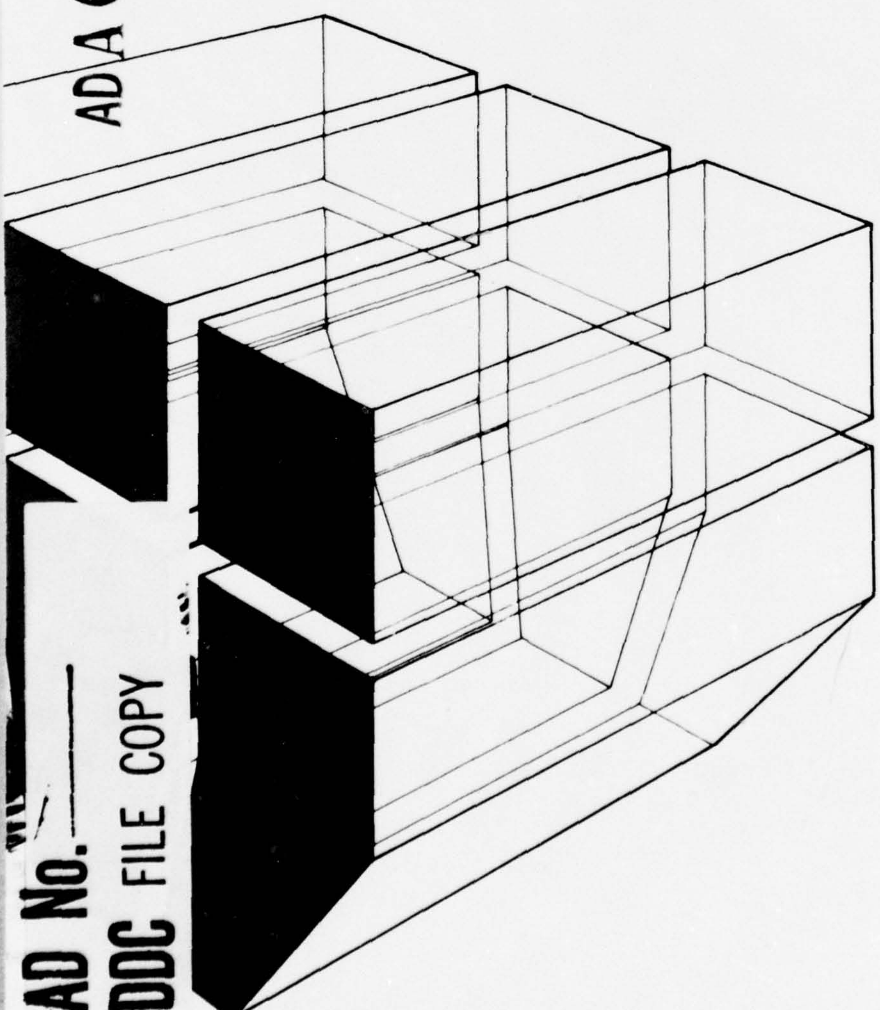
CORROSION COSTS OF AIR FORCE AND ARMY FACILITIES AND CONSTRUCTION OF A COST PREDICTION MODEL



by
Christopher Hahin

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The facility maintenance organizations of several Air Force and Army installations were analyzed to determine the percentage of their direct maintenance, repair or replacement efforts that were corrosion-related. Also included were the costs of designing and inspecting corrosion-related construction projects. This raw data was processed and correlated with climatological, geographic and environmental statistics to develop a predictive corrosion cost model. The resulting empirical equations are able

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to predict facility corrosion costs and classification with reasonable accuracy as a function of installation dimensions and capacities, and readily obtainable weather, soil and air quality data.

FOREWORD

This research was conducted for the Air Force Civil Engineering Center (AFCEC) under Military Interdepartmental Purchase Request #FQ8952-60002, "Economic Evaluation of Air Force Facilities Corrosion." The work was performed by the Metallurgy Branch (MSM), Materials and Science Division (MS) of the U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, IL. The AFCEC Technical Monitor is Mr. H. Stevens, and the CERL Principal Investigator is Mr. C. Hahin.

Additional Army data was derived from Project 4A762719AT41, "Design, Construction, and Operations and Maintenance for Military Facilities," Task T7, "Military Construction Materials," Work Unit 001, "Corrosion Design Guidelines for Fixed Facilities," performed for the Office of the Chief of Engineers, monitored by Mr. C. Damico of DAEN-MCC-C.

The Principal Investigator wishes to acknowledge the following persons who have provided data or assistance during the course of the research: Mr. G. Gerdes, Ms. D. Stevens, Mr. R. Neathammer, and Mr. S. Hathaway, all of CERL; Dr. R. Heidersbach, University of Rhode Island; the officers, supervisors, and personnel of the Base Civil Engineering Squadrons of Chanute, Tinker, MacDill, and Griffiss AFBs, and the Facility Engineering Directorates of Ft. Sheridan, Pacific Area of the Canal Zone, and Ft. Polk; Mr. T. McMullen, Office of Air Quality and Standards, Environmental Protection Agency; Mr. B. Carlson, HARCO Corp.

Dr. A. Kumar is Chief of MSM, and Dr. G. Williamson is Chief of MS. COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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SECTION I

INTRODUCTION

Although the military services have long recognized the economic drain that corrosion represents (References 1-4), a comprehensive, in-depth analysis of corrosion-related facility maintenance costs has never been undertaken. Because corrosion costs constitute a significant portion of the operations and maintenance (O&M) budget, knowledge of (1) where these costs lie, (2) their extent, and (3) their predictability is desirable for military planners and facility maintenance managers.

In recent years, the prices of construction materials have risen substantially, compared to the era of relative price stability from 1955 to 1965 (Reference 5). (See Figures 1a and 1b.) Similarly, construction wages, compared to nonagricultural and manufacturing wages, increased their disparity in the past few years. (See Figure 2.) The prices of fuels contained by pipelines and other storage vessels subject to leakage induced by corrosion have also increased sharply due to political and economic pressures. (See Figure 3.) Thus, the cost of replacing corroded components or their contents has become even greater.

Projected U. S. requirements for the year 2000 for steel, copper, aluminum, and zinc reflect a doubling of present output, and the demand for total energy slightly greater than twice current requirements. Projected world demand for these primary metals for the year 2000 is even greater than U. S. needs (Reference 6).

During the post-World War II era, an expansion and modernization of U.S. military bases was undertaken, resulting in comparatively new fixed facilities, especially for the Air Force. In FY 64, approximately 1.9 percent of the

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1 Department of the Army, "Economics of Corrosion Control," *TM5-811-4 Electrical Design: Corrosion Control*, 1 August 1962, pp 2-16.

2 Department of the Navy, "Importance of Corrosion," *NAVDOCKS MO-306 Corrosion Prevention and Control*, June 1964, pp 1-2.

3 L. West and T. Lewicki, "Justification for Corrosion Control," *AFCEC-TR-74-6 Vol I Civil Engineering Corrosion Control - General*, January 1975, pp 2-13.

4 Department of Defense, "Corrosion and Engineering Design," *MIL-HDBK-721 (MR) Corrosion and Corrosion Protection of Metals*, November 1965, p 1.

5 Council of Economic Advisors, *Economic Report of the President*, February 1975, Tables C-49, C-30, and 23, pp 306, 284, and 84.

6 W. Malenbaum, C. Cichowski, and J. Riordan, *Materials Requirements in the U. S. and Abroad in the Year 2000*, (NTIS Report PB-219), Wharton School of Finance, March 1973, pp 34-35.

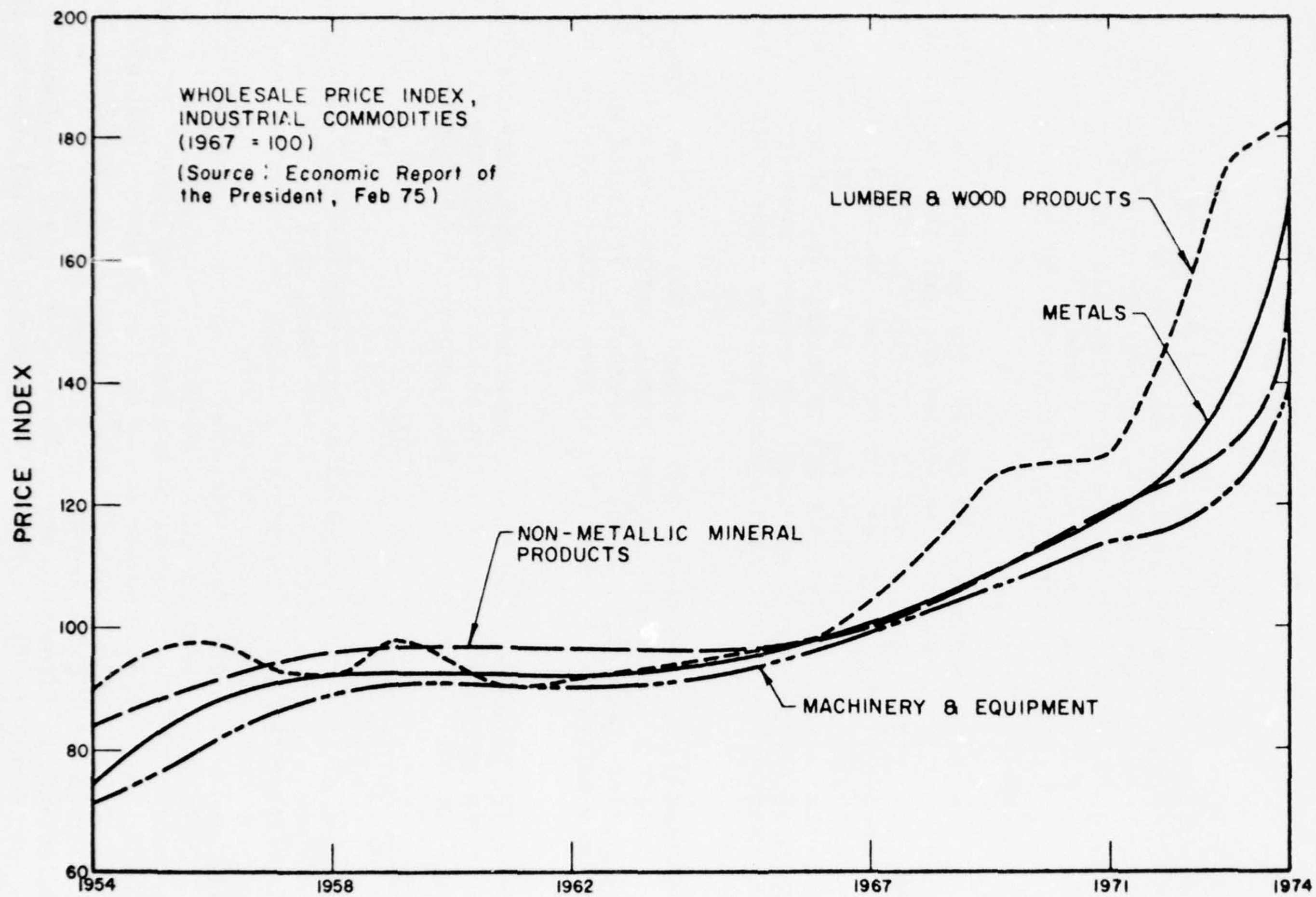

Figure 1a. The Wholesale Price Index of Composite Prices for Various Commodities Since 1955 (1967 = 100).
Source: *Economic Report of the President, 1975.*

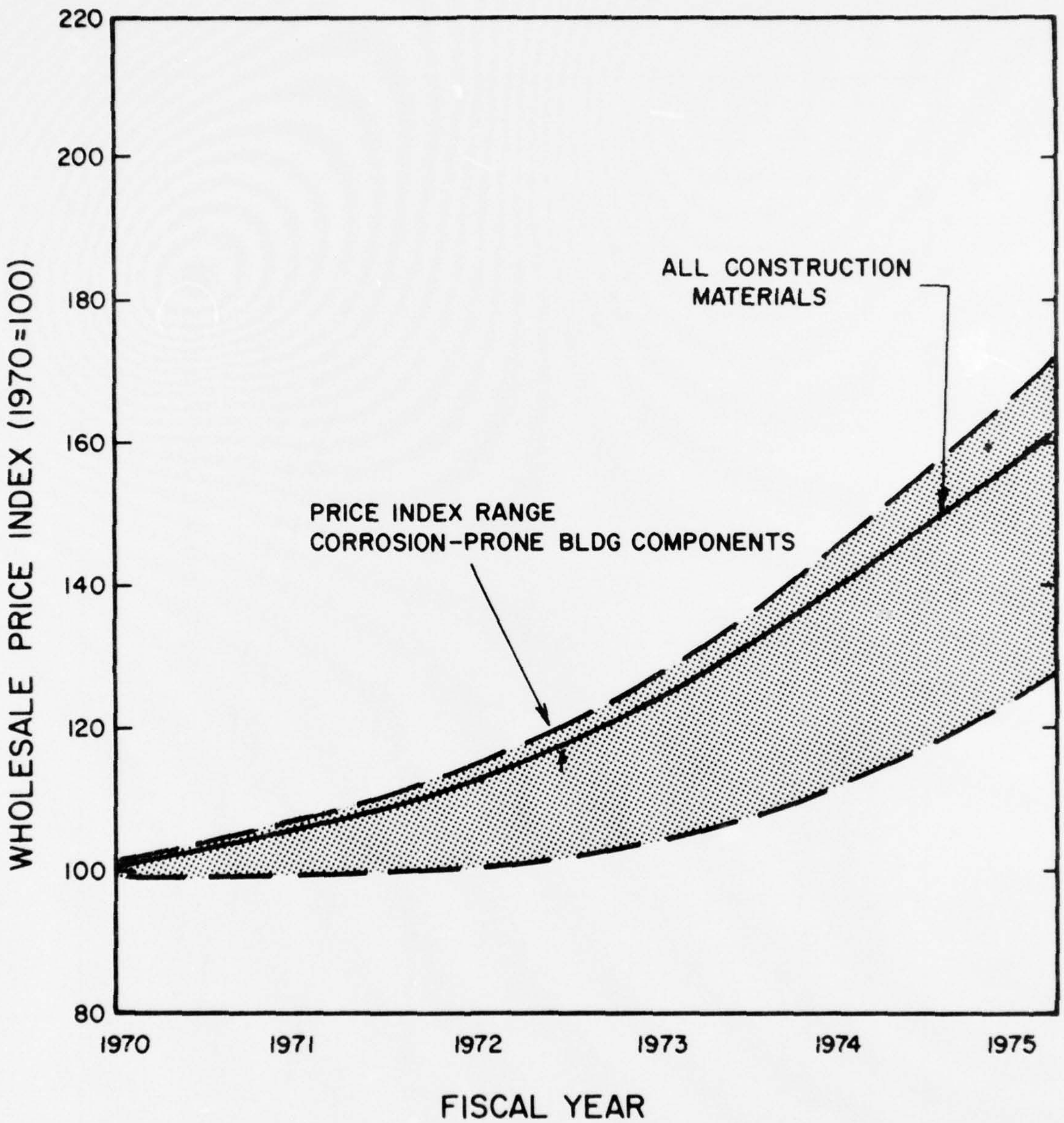

Figure 1b. Price Index Range of Key Building Materials Subject to Corrosive Deterioration With the Price Index of All Building Materials Plotted Within the Wholesale Price Index Range Bands. (Range Band Consists of Wholesale Price Indexes for Reinforcing Bars, Galvanized Steel Sheets, Builder's Hardware, Brass Fittings, Heating Equipment [Including Steam and Hot Water, Warm Air Furnaces and Water Heaters], and Aluminum Siding.) Data Source: U. S. Department of Commerce, "Building Materials," *U. S. Industrial Outlook 1976*, January 1976, Table 1, p 14.

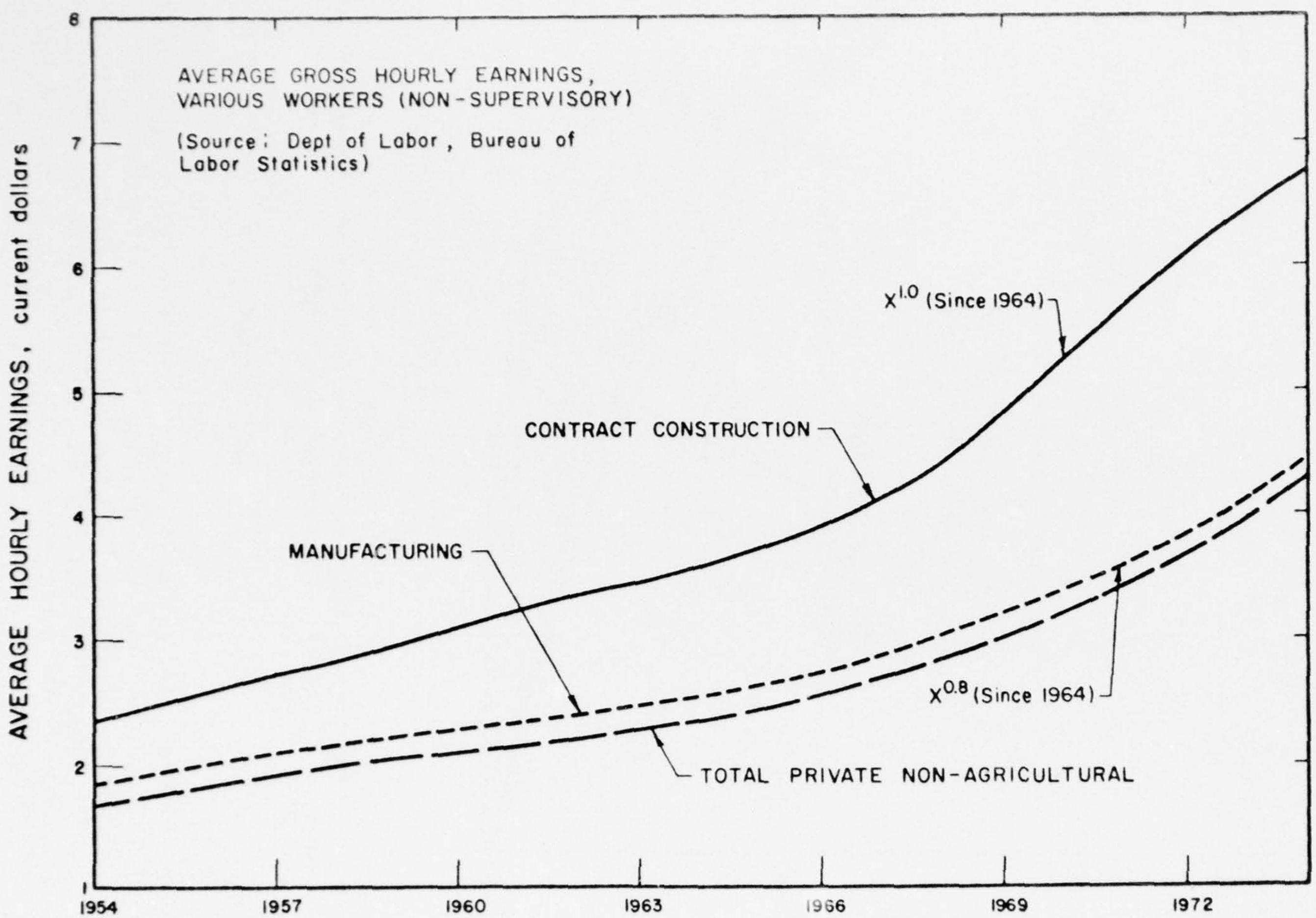

Figure 2. Comparison of Average Hourly Wage Earnings for Construction, Manufacturing, and Nonagricultural Workers in Recent Years.

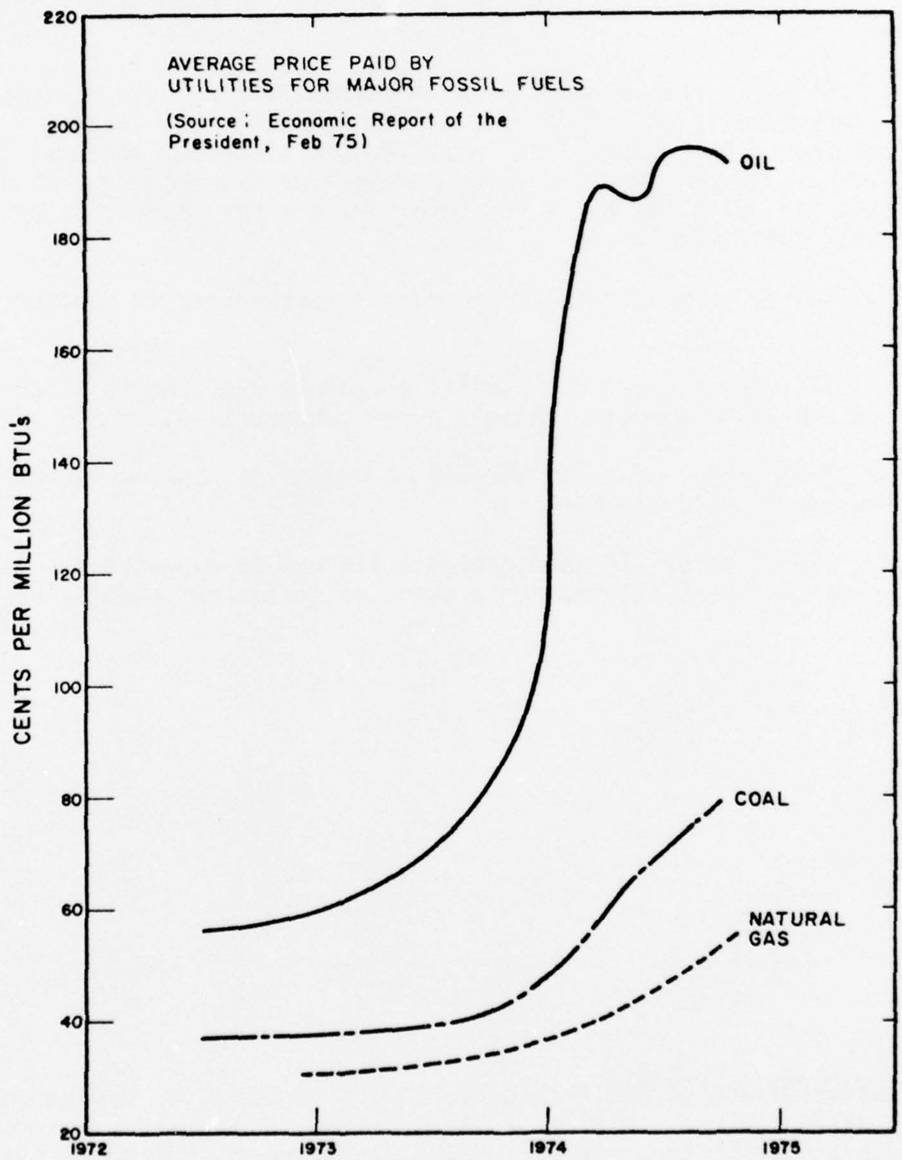

Figure 3. Recent Price Increases for Key Energy Sources.

defense budget went toward Military Construction; this has held steady at 1.8 percent in FY 77 (Reference 7). Likewise, O&M expenditures increased from 23.1 percent in FY 64 (Reference 8) to 30.5 percent in FY 77. Although part of these O&M expenditures is intended for weapon systems, the remainder goes toward fuels and O&M of facility systems. New facilities are being built at the same rate as in FY 64, supplementing aging facilities requiring maintenance, partly due to corrosion. Therefore, as a conservative estimate, corrosion-related expenditures for facility systems are not expected to decrease if present trends continue.

It also seems that present General Purpose and Reserve National Guard Force levels (Reference 9) are to be kept fairly stable in the future, requiring sufficent basing of these forces on installations dispersed throughout the United States and on foreign soil. The Army represents the majority of these general purpose forces, with the Air Force holding a greater proportion of strategic forces than the other services.

In summary, present defense spending trends appear to support the following conclusions:

(1) O&M expenditures for facilities can be expected to slightly increase in the future to accommodate aging and new construction.

(2) Projections of an unprecedented number of base or installation closings seem unwarranted at this time.

(3) Labor, materials, and energy costs can be expected to rise in the long run, making corrosion-related replacement of system components increasingly costly.

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7 Executive Office of the President, *Budget of the U. S. Government, Fiscal Year 1977*, p 62.

8 J. Schlesinger, *Annual Report of the Secretary of Defense to the Congress for FY 1976 and FY 197T*, 5 February 1975, Appendix D, Table 1, p D-1.

9 D. Rumsfeld, *Annual Report of the Secretary of Defense to the Congress for FY 1977*, 27 January 1976, Appendix B, Table 2, p 271.

SECTION II

PLAN TO ACHIEVE THE RESEARCH OBJECTIVE

The objective of this AF research study was to gather raw cost data by field survey, process it, and then develop an accurate predictive model which could determine actual corrosion costs. Such a model will permit channeling of further research efforts into areas of greatest pay-off (Reference 10).

A complementary Army research work unit (Reference 11), whose objective was to identify corrosion-intensive designs, materials, and construction procedures associated with military facilities in order to improve guide specifications, also provided data input for the model.

The overall approach was to develop a set of procedures to achieve the defined objective, consisting of the following:

(1) AF and Army installations of varying mission, topography, and location were selected as survey sites.

(2) Corrosion-related costs were determined by inspection of the nature of the work performed by AF Civil Engineering Squadrons and Army Facility Engineers. Specific criteria was developed to establish which costs were corrosion-related, as opposed to wear, fatigue, mechanical overload, or similar system dysfunction. Distinctions were made between the deterioration of metallic and non-metallic components. Other work, such as modification, repair, or construction to accommodate increased force levels or changes in mission, was considered as not corrosion-related.

(3) Predictive relationships were developed between the factors of climate, topography, environment, and the costs of corrosion. Corrosion costs were also compared with facility system capacities and dimensions common to all DOD installations. Finally, these costs were categorized, and equations were developed to predict the percentage of total corrosion costs for each category.

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10 Air Force Civil Engineering Center, *Military Interdepartmental Purchase Request Number FQ8952 60002* (DD Form 448), 13 June 1975, p 1.

11 Army Construction Engineering Research Laboratory, "Corrosion Abatement Design Criteria," *Research and Technology Work Unit Summary* (DD Form 1498), 1 December 1975.

SECTION III

COST ANALYSES OF AIR FORCE AND ARMY INSTALLATONS

DETERMINATION OF CORROSION COSTS AT AF INSTALLATIONS

The work records of the Civil Engineering organizations (References 12-15) at four AF bases and one remote station (Reference 16) were analyzed for two nonsequential months out of a fiscal year. In these surveys, the amount of available labor resources for O&M work centers that was expended on operating or maintaining corroding facilities was determined by inspection of Daily Work Logs, Maintenance Action Sheets, and shop interviews. The amount of labor time spent on corrosion-related work compared to total available time resulted in a corrosion percentage* for that work center. This percentage could be applied against either total work center costs or just labor costs obtained from the Responsibility Center Manager Cost Report.

Additionally, construction contracts were analyzed to determine if they were or were not attributable to corrosion. The corrosion-related portion of construction contracts was compared to the total value of all non-runway-related contracts for 10 years (if data were available). To compensate for inflation, the Engineering News-Record Index was applied to compare costs of previous years with a baseline fiscal year (FY 74). The average construction contract corrosion percentage for a 10-year span was calculated as:

$$\frac{\Sigma \text{ annual construction corrosion costs, FY 74\$}}{\Sigma \text{ annual construction value, FY 74\$}} \times 100 = c_{const}$$

This method of calculation was used because of sharp fluctuations in construction contract appropriations from year to year. Documents analyzed include DD Form

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12 R. Heidersbach and W. Mikucki, *Corrosion Cost Survey of Chanute AFB*, Construction Engineering Research Laboratory (CERL) Letter Report M-89, April 1974 (unpublished).

13 R. Heidersbach, W. Mikucki and G. Gerdes, *Corrosion Cost Survey of MacDill AFB*, CERL Letter Report M-91, July 1974 (unpublished).

14 R. Heidersbach, W. Mikucki and G. Gerdes, *Corrosion Cost Survey of Tinker AFB*, CERL Letter Report M-100, January 1976 (unpublished).

15 R. Heidersbach and R. Turcotte, *Corrosion Cost Survey of Griffiss AFB*, Battelle-Columbus Task Order Report 76-133 (Scientific Services Program), April 1976 (unpublished).

16 C. Hahin and G. Gerdes, *Corrosion Cost Survey of Calument AFS*, CERL Letter to AFCEC, April 1976 (unpublished).

*NOTE: The corrosion percentage is referred to as a "corrosion multiplier" in the AF base surveys.

1391 Military Construction Project, SF 23 Construction Contract, SF 30 Amendment of Contract, and various other project file documents, including plans and specifications if further clarification was required.

The AF surveys considered several categories of work as corrosion related:

(1) Functional degradation (loss of use) of metallic components, necessitating repair or replacement.

(2) Failure of corroded metal components causing deterioration of non-metallic components, such as pipe leakage damaging gypsum wallboard.

(3) Degradation of non-metallic utility piping.

(4) Removal of scale or replacement of scaled equipment.

DETERMINATION OF CORROSION COSTS AT ARMY INSTALLATIONS

In similar, independent studies (References 17-19) of Army installations, the Facility Engineer organization was analyzed to determine which work sections were corrosion intensive. This was accomplished by conducting extensive interviews with supervisors, reviewing job descriptions, discussing corrosion time allocations with workers, and analyzing the Annual Work Plan. The percentage of effort devoted to combating corrosion was applied against total labor and materials obtained from the Annual Work Plan, resulting in an annual corrosion cost. Construction contracts were also examined to determine which projects had corrosion as their root or partial cause. Contracts over a period of 3 to 5 years were evaluated, including Military Construction Army (MCA), maintenance and repair (M&R) projects, and minor Purchase Orders.

The significant differences between the Air Force and Army surveys were the analysis of material costs and a slightly different interpretation of what was considered corrosion-related work. During the first Army survey, all Job Orders for one fiscal year were analyzed to note whether materials had the same corrosion percentage as labor. About 14.9 percent of total labor was corrosion related, whereas corrosion-related materials were 12.2 percent of total materials. Therefore, applying the corrosion *labor percentage against materials costs* was justified, since labor and materials percentages are proportional.

Work designated in the Army surveys as corrosion related met the following criteria:

17 C. Hahin, *Facility Engineer Corrosion-Related Costs and Trends at Fort Sheridan, IL*, CERL Letter Report M-146, July 1975 (unpublished).
18 C. Hahin, *Corrosion-Intensive Military Facility Systems in the Canal Zone*, CERL Letter Report M-173, February 1976 (unpublished).
19 C. Hahin, *Design Implications for Corrosion Related Problems at Ft. Polk, LA*, CERL Letter Report, 21 June 1976 (unpublished).

(1) Involved failure or deterioration of a metallic system or one that contained metal parts subject to corrosive attack.

(2) Involved damage to non-metallic systems or buildings caused by failure of a metallic system (viz: water line leaks caused by corrosion in a building, which damaged walls or floors).

(3) Involved actions required to prevent metal systems (or those containing metal) from corroding, such as boiler treatment, painting, or cathodic protection.

Oxidation from gases (high or low temperature) or attack of metal surfaces by the incomplete combustion of hydrocarbons was also considered corrosive, although mechanical wear of a part which is constantly lubricated was not considered environmental degradation since water, gases, or corrosives are normally assumed to be excluded.

SIMILARITY OF ARMY AND AF ENGINEER ORGANIZATIONS

AF Regulation 85-10 prescribes the typical Base Civil Engineer (BCE) organizational structure, which varies somewhat from base to base. Major commands can optionally permit other work centers to be operational, depending on local conditions. The base mission(s) will dictate which facility systems are required for support.

The Army Facility Engineer (FE) organization is very similar in structure. The distinguishing features of the BCE organization are the separate break-out of the Programming function, whereas the FE keeps this function under an engineering jurisdiction.

The physical layouts of AF bases and Army installations are also very similar and this commonality forms the basis for a joint cost model. Costs can be expressed in terms of corrosion percentages for each work center or section, or in corrosion cost per unit dimension or capacity.

The corrosion percentages for each work center (AF nomenclature) or comparable Army section for the seven major installations surveyed are summarized in Table 1. Table 2 lists actual corrosion costs and relative percentages of overall effort compared to operating budgets for the installations. In Table 3, the percent of in-house corrosion-related effort is compared with corrosion-related contract work.

CATEGORIZATION OF CORROSION COSTS

As a further method of comparison, the various work center corrosion costs were placed into AFCEC preselected categories of (1) underground corrosion, (2) potable waters, hot and cold, (3) steam condensate, (4) atmospheric and protective coatings, (5) high temperature and boilers, (6) air conditioners,

TABLE 1. SUMMARY OF CORROSION PERCENTAGES FOR WORK CENTERS*

AF Work Center	Army Section Equivalent	AF Bases				Army Installations		
		1	2	3	4	5	6	7
Plumbing	Plumbing	17.6	42.9	26.3	5.8	72.1	50.0	40.0
Heating Systems	Boiler Plants; Heating Systems	29.0	11.2	39.2	41.0	20.9	NDA	8.4
Refrigeration and Air Conditioning	Refrigeration and Air Conditioning	13.8	14.4	12.6	24.0	10.0	19.0	7.9
Exterior Electric	Exterior Electric	1.0	19.3	9.0	0.1	17.2	24.0	24.0
Interior Electric	Interior Electric	1.0	5.1	2.2	2.7	2.9	26.0	15.0
Structures Maint.	Carpentry	3.2	33.8	6.1	1.8	1.9	55.0	5.0
Protective Coatings	Painting	1.5	17.6	5.3	1.2	10.5	NDA	7.5
Metal Working	Metal Working	5.6	22.1	15.4	10.2	16.0	15.0	12.5
Water and Waste	Water Plant; Sewage Plant	5.8	5.8	3.6	5.8	3.3 29.7	NDA	14.0
Liquid Fuels	Fuel Storage and Issue	1.0	53.0	8.6	30.0	NDA	NDA	NDA
Power Production	None	NDA	16.7	16.9	5.2	-	-	-
SMART	Preventive Maint.	NDA	-	-	4.6	5.4	NDA	26.0
Pavements, Grounds, Equipment Operations	Pavements, Grounds, and Organizational Maintenance	7.5	0.4	2.6	2.2	11.4	5.9	0.0
Programs; Engineering and Construction	Engineering Plans and Services	12.7	18.1	15.3	8.8	15.6	37.0	9.7

TABLE 2. ACTUAL ANNUAL CORROSION COSTS IN THOUSANDS OF 1975 DOLLARS[a]

Installation/ Service	Total Corrosion-Related Expenditures (L + E + M + C)[b]	Total Available Expenditures (L + E + M + C)[b]	Overall Corrosion %
Chanute/AF	975.2	11,404.5	8.6
MacDill/AF	1,345.8	9,351.6	14.4
Tinker/AF	1,678.4	16,018.4	10.5
Griffiss/AF	988.7	16,119.0	7.7
Sheridan/Army	682.6	5,133.2	13.3
Amador/Army	2,455.7	10,173.1	24.1
Polk/Army	810.8	7,383.9	11.0

[a]NOTE: Figures in this table have been adjusted to 1975 dollars by applying the ratio of the ENR Composite Index of Dec 1975 to the ENR Composite Index for the time in question.

[b]L = labor; E = equipment; M = materials; C = maintenance and repair contracts (non-MCP).

TABLE 3. IN-HOUSE VS CONTRACT CORROSION-RELATED WORK

Installation/ Service	Corrosion % of Total In-House Effort (O&M)	Corrosion % of Total Contract Effort[a]
Chanute/AF	7.6	12.7
MacDill/AF	11.8	18.1
Tinker/AF	9.1	15.3
Griffiss/AF	7.3	8.8
Sheridan/Army	12.5	15.6
Amador/Army	25.9	37.0
Polk/Army	11.9	9.7

[a]Restricted to maintenance and repair contracts; MCP or MCA excluded.

air and water exchange, and (7) miscellaneous other. By sorting the efforts of work centers into the various categories, the categorized costs and their relative percentages compared to total O&M corrosion costs for each installation are provided in Tables 4 and 5.

TABLE 4. CORROSION COST BY CATEGORY

(In Thousands of Dollars, Adjusted to 1975 = 100)

Installation	Type	Underground	Potable Water	High Temperature Oxidation & Boilers	Condensate	Atmospheric & Protective Coatings	Refrigeration & Air Cond.	Misc.
Chanute	O&M	90.3	45.5	201.5	192.5	71.7	70.4	0
	MAREMIC[a]	63.5	28.5	85.8	44.6	53.6	27.2	0
	MCP*	67.4	30.3	91.3	47.4	57.1	28.9	0
MacDill	O&M	115.5	62.1	34.1	10.3	576.7	103.7	0
	MAREMIC[b]	33.1	18.7	14.3	0	316.3	61.0	0
	MCP*	14.0	7.9	6.0	0	133.5	25.7	0
Tinker	O&M	96.1	80.4	190.4	287.8	252.4	220.2	6.3
	MAREMIC[c]	94.0	29.0	42.2	84.8	107.9	165.7	21.2
	MCP*	312.8	95.8	141.0	282.0	358.0	549.6	70.5
Griffiss	O&M	57.3	30.6	523.0	50.2	79.4	97.0	0
	MAREMIC[g]	136.9	15.7	17.6	88.1	147.5	2.3	0
Sheridan	O&M	201.5	51.5	96.7	0.9	98.7	13.2	0
	M&R[d]	73.3	6.4	96.3	5.3	34.0	4.8	0
Amador	O&M	152.1	96.2	61.5	0	838.2	198.2	0
	M&R[e]	7.4	41.3	7.7	0	942.7	110.4	0
Polk	O&M	250.7	15.6	6.4	0	224.8	21.9	0
	M&R[f]	192.7	7.1	18.1	0	73.5	0	0

[a]Ten-year project averages.
[b]Five-year project averages.
[c]Eight-year project averages.
[d]Five-year project averages.
[e]Three-year project averages.
[f]Three-year project averages.
[g]Six-year project averages.

*The overall corrosion construction percent for MAREMIC was applied against Military Construction Program (MCP) in the original surveys of AF bases to accommodate aging of facilities replaced. This optional indirect cost is not considered in calculations of overall percentages in this report. MAREMIC projects consist of maintenance, repair, and minor construction, but do not include major MCP projects which are of command or Congressional origin due to mission changes or expansions.

TABLE 5. CORROSION COST BY CATEGORY, PERCENT OF TOTAL ANNUAL COST

Installation	Under-ground	Potable Water	High Temperatures and Boilers	Condensate	Atmospheric	Refrigeration and Air Conditioning	Miscel-laneous
Chanute	15.8	7.6	29.5	24.3	12.8	10.0	0
MacDill	11.0	6.0	3.6	0.8	66.4	12.2	0
Tinker	11.3	6.5	13.9	22.2	21.5	23.0	1.6
Griffiss	15.6	3.7	43.4	11.1	18.2	8.0	0
Sheridan	40.3	8.5	28.3	0.9	19.4	2.6	0
Amador	6.5	5.6	2.8	0	72.5	12.6	0
Polk	54.7	2.8	3.0	0	36.8	2.7[a]	0

[a]This percentage is abnormally low because no refrigeration contracts were let during the 3-year period analyzed.

SECTION IV

DEVELOPMENT OF A JOINT SERVICE CORROSION COST MODEL

The total corrosion costs for military facility systems consist of (1) O&M labor and material costs, (2) construction contract costs (confined primarily to maintenance and repair contracts), and (3) energy losses. The model will be pieced together in this sequence, relating why and how well one corrosion variable correlates to other independent variables. Energy losses are to be treated in a separate report.

CORRELATION OF CORROSION DATA WITH CLIMATE, TOPOGRAPHY, AND ENVIRONMENT

Work centers selected for inclusion in the cost model consistently are engaged in corrosion-related work, even though several percentages may be very low. In addition, the independent variables that were correlated had to logically relate to the systems or building components maintained by that work center or section. The predictor variables also had to directly or inversely relate to a high or low percentage, as expected by accepted corrosion principles.

Basic climatic, geographic, and environmental data about the installations surveyed were collected from various authoritative sources. Table 6 summarizes the mean annual temperatures, rainfall, relative humidities, and dew points of nearby weather stations for the bases or installations. Table 7 lists high, mean, and low soil resistivity readings for these installations, if available. Table 8 summarizes water quality of treated potable water. Table 9 reflects the total sulfur oxide (SO_x) emissions and ambient SO_2 concentrations for the Air Quality Regions in which these installations are located for 1974-5, approximately the time the surveys were performed. Table 10 lists the system dimensions or capacities for the various installations studied.

Standard statistical symbols and terminology employed in elementary correlation analysis (Reference 20) are used throughout the text:

$^{1}S_{esty}$ = 1 standard error of estimate of y from the regression line

r = Pearson correlation coefficient

$\pm$ = range of the error, incorporated into the linearized equation.

PLUMBING

The plumbing activity at both AF and Army installations is responsible for removal, replacement, repair, and installation of water and gas lines, plumbing

20 R. Runyon and A. Haber, "Correlation, Regression and Prediction," *Fundamentals of Behavioral Statistics*, Addison - Wesley, 1968, pp 80-105.

TABLE 6. SUMMARY OF CLIMATIC DATA

Installation & Service	Nearest Reporting Weather Station	Air Mass - Source[a] Climatic Classification	Mean Annual[b] Temperature, °F	Mean Relative[b] Humidity	Annual[b] Precipitation, inches	Mean[b] Dew Point, °F
Chanute (AF)	Rantoul, IL	Humid continental	52.7	71.8	37.0	40.8
MacDill (AF)	Tampa, FL	Humid subtropical	72.2	75.8	51.6	62.8
Tinker (AF)	Oklahoma City, OK	Humid continental	61.2	65.7	32.6	45.7
Griffiss (AF)	Syracuse, NY	Humid continental	48.0	71.0	37.6	35.6
Sheridan (Army)	Evanston, IL	Humid continental	49.4	65.8	33.8	39.0
Amador (Army)	Ft. Clayton, Panama Canal Zone	Wet equatorial	79.0[c]	96.0[c]	100[c]	73.5[c, d]
Polk (Army)	Alexandria, LA	Humid subtropical	66.2	78.0	51.3	55.8

[a]A. Strahler, "Climate Classification and Climatic Regionals," *Introduction to Physical Geography*, Wiley, 1970, pp 121-136.

[b]Environmental Science Services Administration, US Dept of Commerce, *Climatic Atlas of the United States*, Superintendent of Documents, 1968.

[c]US Army Tropic Test Center Staff, *Materiel Testing in the Tropics*, US Army Tropic Test Center Report 750 3001, June 1975, p 19.

[d]Average of Atlantic, Mid-Isthmus and Pacific side in wet and dry seasons.

TABLE 7. SOIL RESISTIVITY DATA

Installation	Soil Resistivity, ohm-cm High	Low	Mean
Chanute[a]	10,600	3,000	4,165
MacDill[b]	300,000	110	1,000-2,000
Tinker[c]	26,100	525-2000	2,900
Griffiss[d]	720,000	4,200	109,000
Sheridan[e]	7,000	1,100	3,000
Amador	NDA	NDA	NDA
Polk[f]	101,000	220	19,550

[a]Civil Engineering Corrosion Analysis Team, *Corrosion Survey - Chanute AFB, IL*, AF Civil Engineering Center, Tyndall AFB, FL, 20 May - 2 June 1972, p 7.

[b]Civil Engineering Corrosion Analysis Team, *Corrosion Survey - MacDill AFB, FL*, AF Civil Engineering Center, Wright-Patterson AFB, OH, 9-29 January 1971, p 1.

[c]Civil Engineering Corrosion Analysis Team, *Corrosion Survey - Tinker AFB, OK*, AF Civil Engineering Center, Tyndall, AFB, FL, pp 4-5.

[d]*Griffiss AFB Master Plan*, Cathodic Protection Sheet.

[e]HARCO Corp, *Preliminary Corrosion Survey, Utility Systems, Ft. Sheridan, IL*, Chicago District, Corps of Engineers, Contract DACA 23-69-C-0098, August 1969, Appendix 1 (Dwg L-1066).

[f]HARCO Corp, *Corrosion Control Study and Design, Ft. Polk, LA*, Ft. Worth District, Corps of Engineers, Contract DACA 63-75-C-0038, August 1975, Appendix 1A, Table 1, p 2.

NDA = No data available.

TABLE 8. QUALITY OF TREATED POTABLE WATERS[a]

Installation	Hardness, mg/l	pH	Conductivity, μmhos @ 298K	CO_2 ppm	Total Dissolved Solids, mg/l
Chanute	288.5	7.7	533.0	14.0	288.5
MacDill	135.5	7.8	290.0	2.2	203.0
Tinker[b]	187.2	8.0	325.4	7.2	220.0
Griffiss	44.0	6.9	101.0	8.0	68.0
Sheridan	133.0	10.0	260.0	NDA[c]	157.0
Polk[d]	95.3	7.5	330.0	NDA[c]	215.6

[a]Derived from U.S. Geological Survey analyses or Army Environmental Health reports.

[b]Mean value of 24 wells.

[c]NDA = no data available.

[d]Mean value of 14 wells.

TABLE 9. AIR POLLUTION DATA FOR INSTALLATIONS SURVEYED

Installation & Service	Air Quality Region Number	SO_x Emissions,[a] Tons/Year/km^2	Ambient SO_2[b] Concentration, $\mu g/m^3$
Chanute (AF)	66	2.51	NDA[c]
MacDill (AF)	52	29.06	15-65
Tinker (AF)	184	0.30	2-6
Griffiss (AF)	158	1.12	13-48
Sheridan (Army)	67	38.22 (excludes Indiana)	37
Amador (Army)	NA[d]	estimated at 1.00[e]	NDA[c]
Polk (Army)	106	7.13	2

[a]U.S. Environmental Protection Agency, *1973 National Emissions Report*, EPA Document 450/2-76-007, May 1976.

[b]U.S. Environmental Protection Agency, *Monitoring and Air Quality Trends Report, 1974*, EPA Document 450/1-76-001, February 1976.

[c]NDA = no data available.

[d]NA = not applicable.

[e]U.S. Army Tropic Test Center Staff, *Materiel Testing in the Tropics*, U.S. Army Tropic Test Center Report 7503001, June 1975, p 72.

TABLE 10. PHYSICAL DIMENSIONS AND CAPACITIES OF INSTALLATIONS SURVEYED

(Includes Military Family Housing)[a]

System Description and Unit	Chanute AFB	MacDill AFB	Tinker AFB	Griffiss AFB	Ft. Sheridan	Ft. Amador	Ft. Polk
Natural gas and water distribution, KLF	402	494	652	307	269	816	1124
Heating plant capacity, MBtu	1,015,644	59,406	1,571,550	681,447	454,546	61,838	66,341
Total refrigerating capacity, TONS	4877	8158	21,628	4275	2666	9102	9254
Electric distribution lines, exterior, KLF	351	618	639	454	776	1640	1027
Total bldg. surface, all classifications, KSF	4616	3642	11,684	5482	6580	16,156	8551
Water produced, KGAL	57,442	278,838	1,243,812	316,494	398,835	-	797,168
Steam distribution, KLF	143	1	117	100	38	2	38
Electrical generating capacity, emergency, KW	NR[b]	4560	4038	2347	-	-	-
Liquid fuels dispensed, KBBL	21	944	939	1594	-	-	-

[a]Sources: For AF bases, HAF-PRE (SA)-7101 *Civil Engineer Cost Report*, HAF-PRE-AR-7115 *Current Space Inventory by Type of Construction*, and Base Master Plans. For Army installations, *Facilities Engineer Annual Summary of Operations*, FY 1975, pp 85-87, 148-150, 229-231.

[b]NR = not reported

fixtures, and for augmenting other sections by repairing exterior water or steam lines when applicable. The primary physical dimension this function deals with is total linear footage of buried pressurized water and gas lines.

Several variables affect the corrosion rate of buried piping, such as the annual rainfall, soil characteristics, general topography with respect to pipeline routes, or extent of cathodic protection. A single variable which takes these multiple factors into account is the soil resistivity, measured in ohm-cm. Correlations between mean, high, and low resistivity revealed that low resistivity appears to correlate best, rather than mean resistivity, as would be normally expected. This is apparently because high resistivities prejudice the low readings, resulting in a high average. Data plotted in Figure 4 are based on the minimum soil resistivity derived from an entire survey or reports which summarize such information as high, low, and average. Since appreciable corrosion does not occur below 5,000 ohm-cm, the mean of all readings $\leq$ 5,000 ohm-cm is probably the best indicator, if such data can be obtained.

However, if one data point is ignored as anomalous, the correlation is remarkable for corrosion percentage as a function of minimum soil resistivity. The anomalous point (Sheridan) is due to complete lack of cathodic protection and advanced longevity of many buried pipelines, some in excess of 70 years. The other installations had partial cathodic protection and were of moderate age (20 to 30 years).

Figure 5 correlates the corrosion cost per thousand linear feet of gas and water distribution lines for six installations (one anomalous point dropped).

The corrosion percentage and corrosion cost/KLF can be predicted by these equations:

$$C_{pl} \pm 6.1 = 44.3 - 0.00909 \text{ (ohm-cm)} \quad (1)$$

$$\text{Cost/KLF} \pm 21.9 = 62.8 + 2.83\, C_{pl} \quad (2)$$

where C_{pl} = plumbing corrosion percentage

KLF = thousand linear feet

If C_{pl} is set equal to zero, the soil resistivity value for no corrosion is 4,879, or about 5,000 ohm-cm. This is in the range of 5,000-10,000 which is considered as mildly corrosive (Reference 21) for alkaline soils. About 3000 ohms-cm or less is regarded by Romanoff (Reference 22) as a most corrosive soil, which also confirms the general trend of this correlation.

HEATING SYSTEMS

This work center is responsible for the installation, maintenance, and repair of high and low pressure boilers, exterior distribution lines, space

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21 F. Waters, "Soil Resistivity Measurements for Corrosion Control," *Corrosion*, Vol. 8, 1952, p 407.
22 M. Romanoff, *Underground Corrosion*, NBS Circular 579, April 1957, p 11.

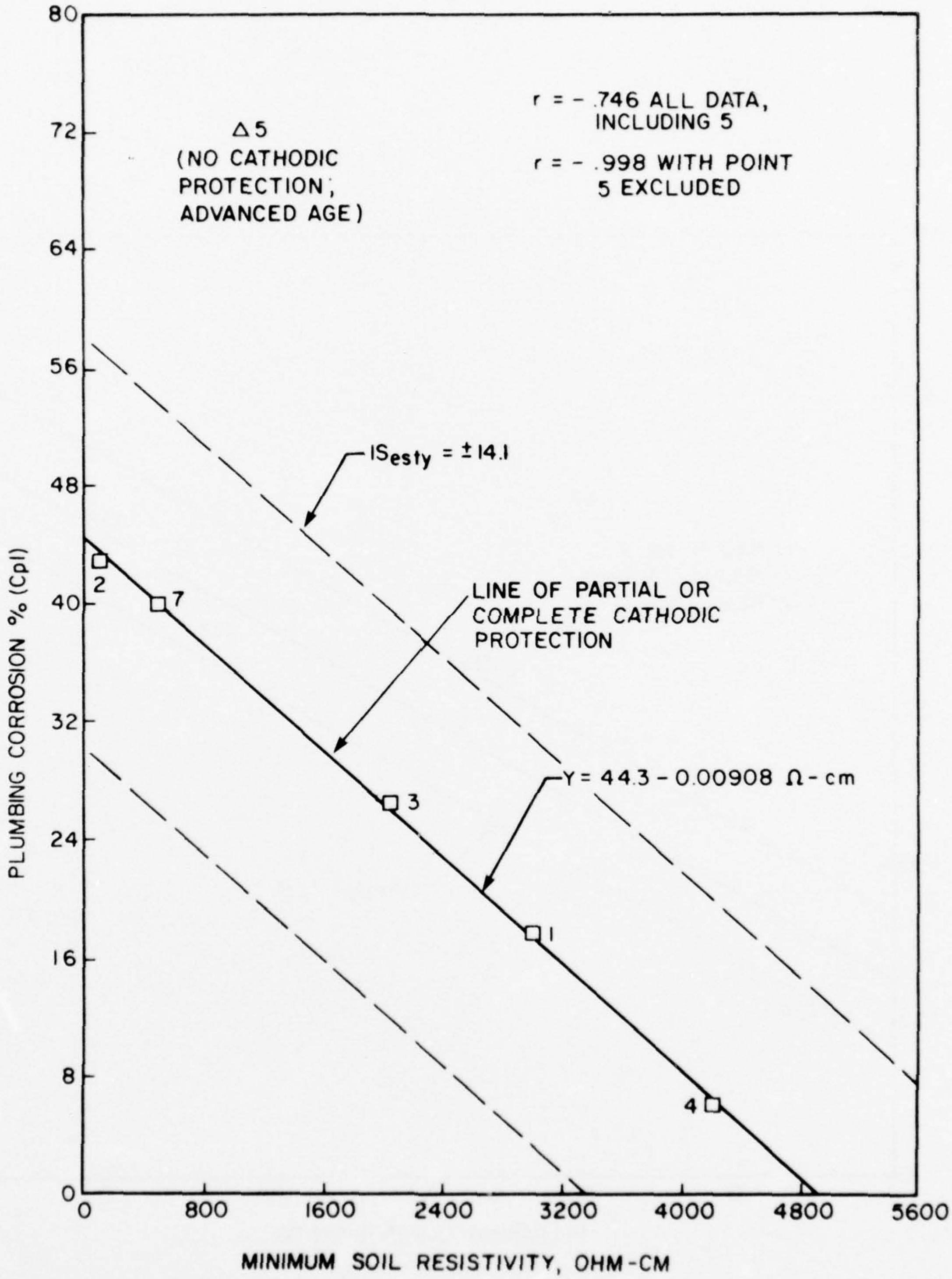

Figure 4. Correlation Between Minimum Soil Resistivity (Obtained by Prior Surveys) in ohm-cm and the Plumbing Corrosion Percentage.

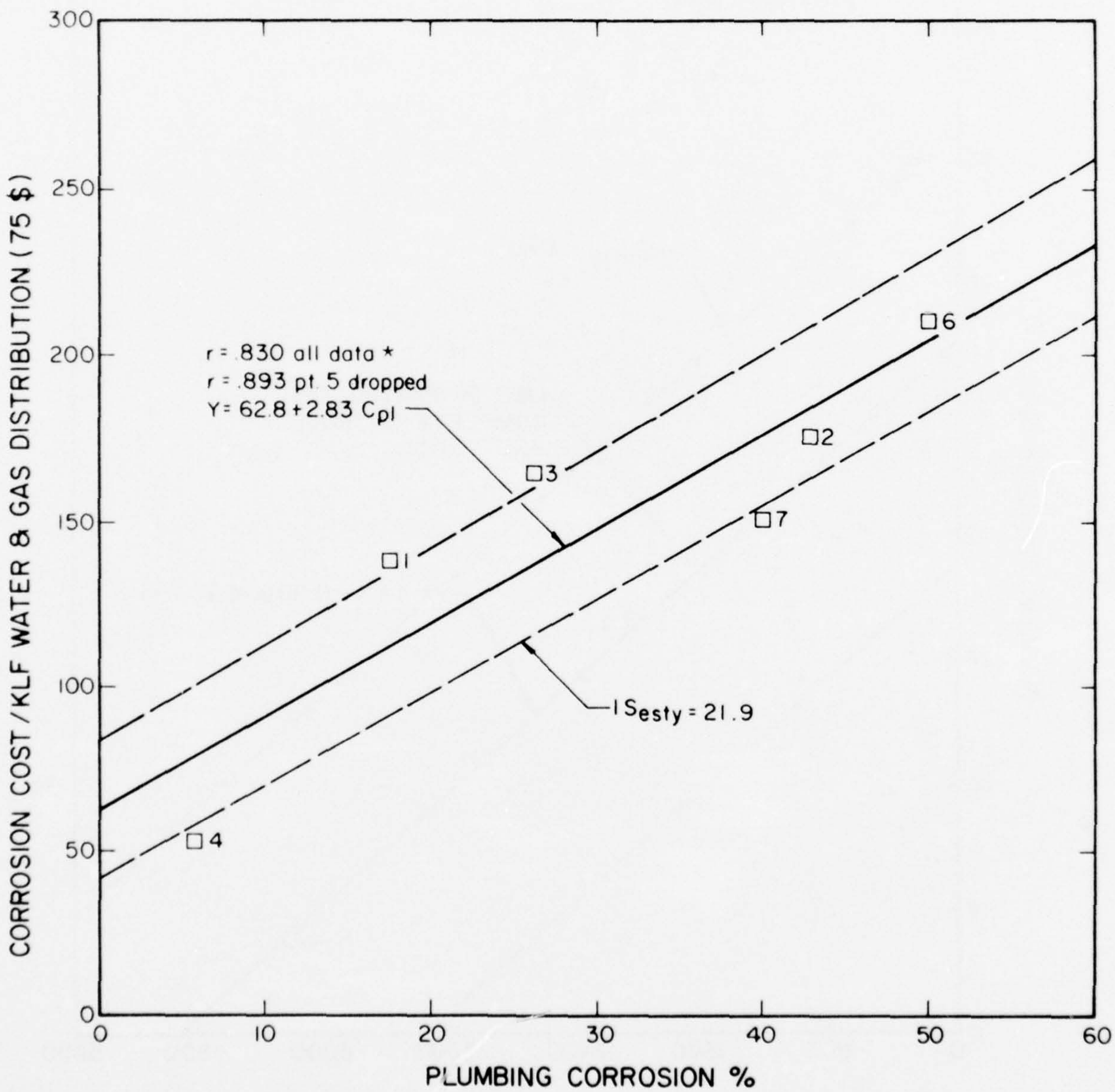

Figure 5. Correlation of Unit Systems Corrosion Cost as a Function of Plumbing Corrosion Percentage (Adjusted for Inflation). *Note: Point 5 is off scale (Sheridan).

heaters, converters, and other heat exchangers. The AF combines supervisory responsibility into one unit whereas the Army splits jurisdictions into distribution systems and high pressure boilers.

Possible variables considered for correlation were mean ambient temperature and soil resistivity, since they influence the frequency of operation and potential for degradation when buried. Ambient temperature + mega Btu capacity divided by temperature proved to be the best predictor variables. The MBtu/T takes into account plant capacity used for other than building occupant comfort (see Figure 6).

The relationship between cost/KLF steam distribution lines and corrosion percentage was good if installations had a distribution network greater than 100 KLF (Figure 7). For installations without substantial boiler capacity, the heating systems function is small since the demand for space heating is limited. Use of the unit cost per KLF is, therefore, applicable only to installations requiring an exterior distribution network.

In summary, the following equation may be used to predict corrosion percentage for heating systems (C_{hs}) from temperature plus MBtu/°F:

$$C_{hs} \pm 5.7 = 53.0 - 0.642T + 0.000799 \frac{\text{MBtu}}{T}$$

Costs per KLF as a function of C_{hs} may be predicted by:

$$\text{Cost/KLF} \pm 483 = -1105 + 141.3\, C_{hs}$$

REFRIGERATION AND AIR CONDITIONING

This work center is responsible for the maintenance and repair of military and domestic refrigeration, cold storage, ice plants, air compressors, and other cooling equipment.

The two climatic variables which affect the corrosion rate of refrigeration equipment are relative humidity and temperature. Relative humidity affects how much moisture will condense on coils or accumulate internally if leaks are present. Relative humidity also influences the amount of corrosion attack of non-refrigerant-loop components, such as housing panels, instruments, or pneumatic controls. Temperatures beyond 70°F accelerate corrosion, cause increased cycling, and also increase refrigerating load, although manpower compensations for these greater requirements may offset an increasing corrosion percentage.

When plotting refrigeration corrosion percentage versus temperature, no correlation results (Pearson correlation coefficient $r = -0.052$), due to two anomalous points. Relative humidity fares much better, since five points lie on a virtual straight line, as shown in Figure 8.

Figure 9 correlates the corrosion cost per total base tonnage as a function of refrigeration corrosion percentage. All data for installations reporting tonnage are plotted, with excellent correlations and reasonable scatter.

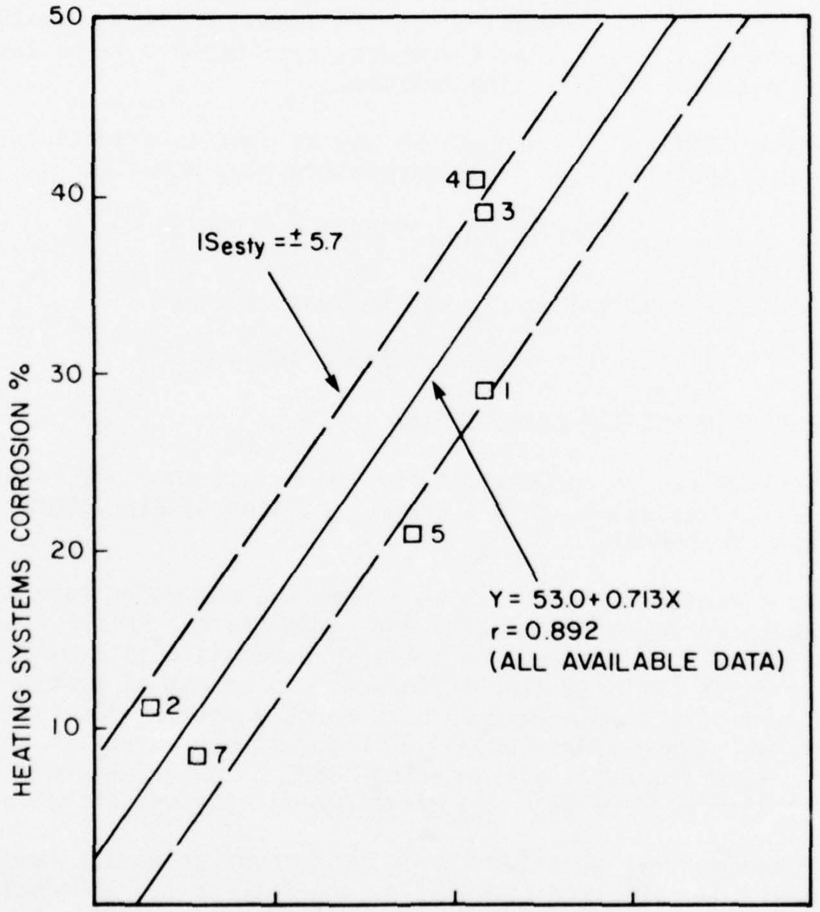

Figure 6. The Heating Systems Corrosion Percentage as a Function of Mean Ambient Temperature and Total Plant Capacity Divided by Temperature (°F + MBtu/°F).

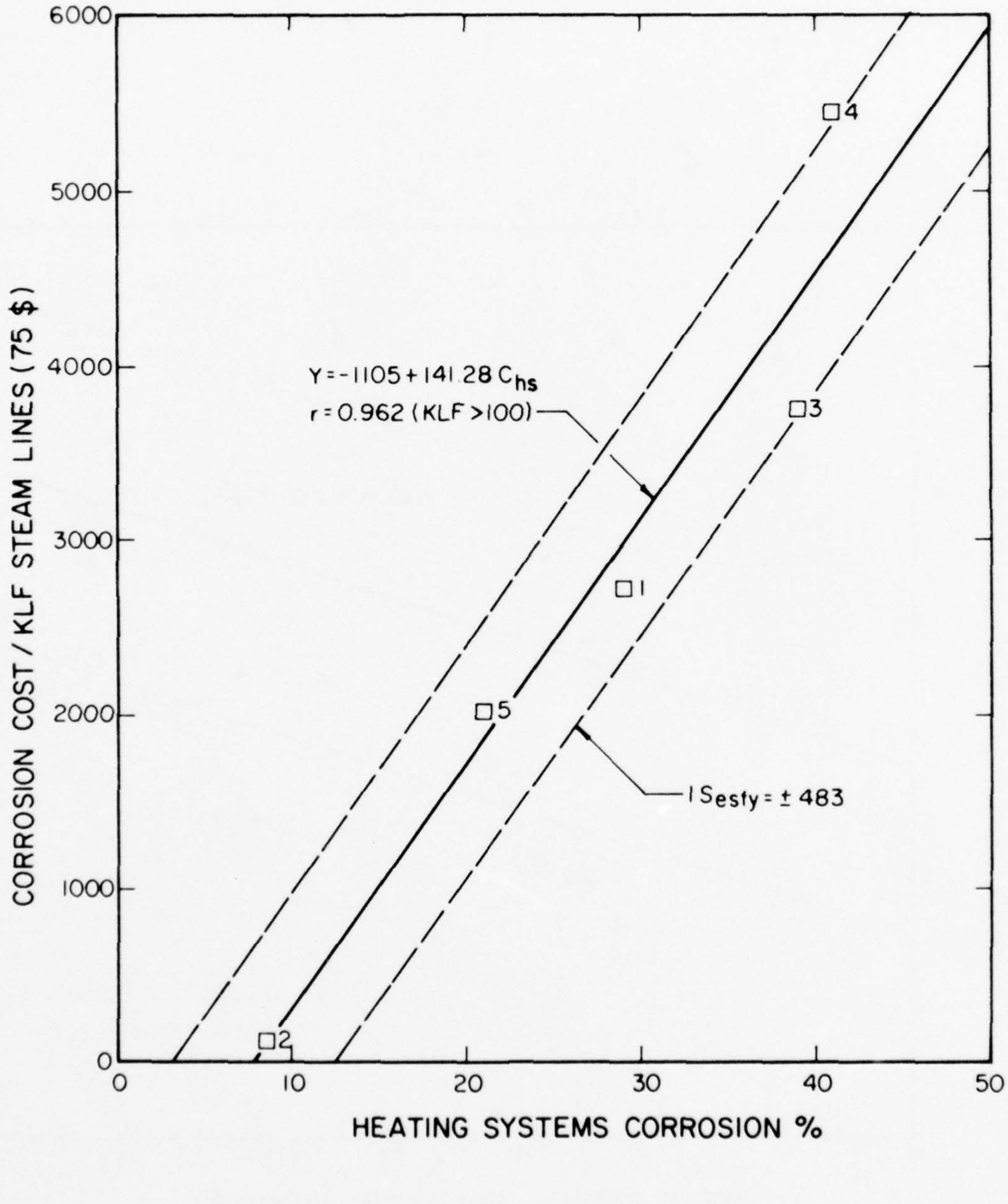

Figure 7. The Corrosion Cost per Thousand Linear Feet of Steam Lines as a Function of the Heating Systems Corrosion Percentage. (Data Points Plotted are Only for Installations Having Distribution Systems in Excess of 100,000 Linear Feet.)

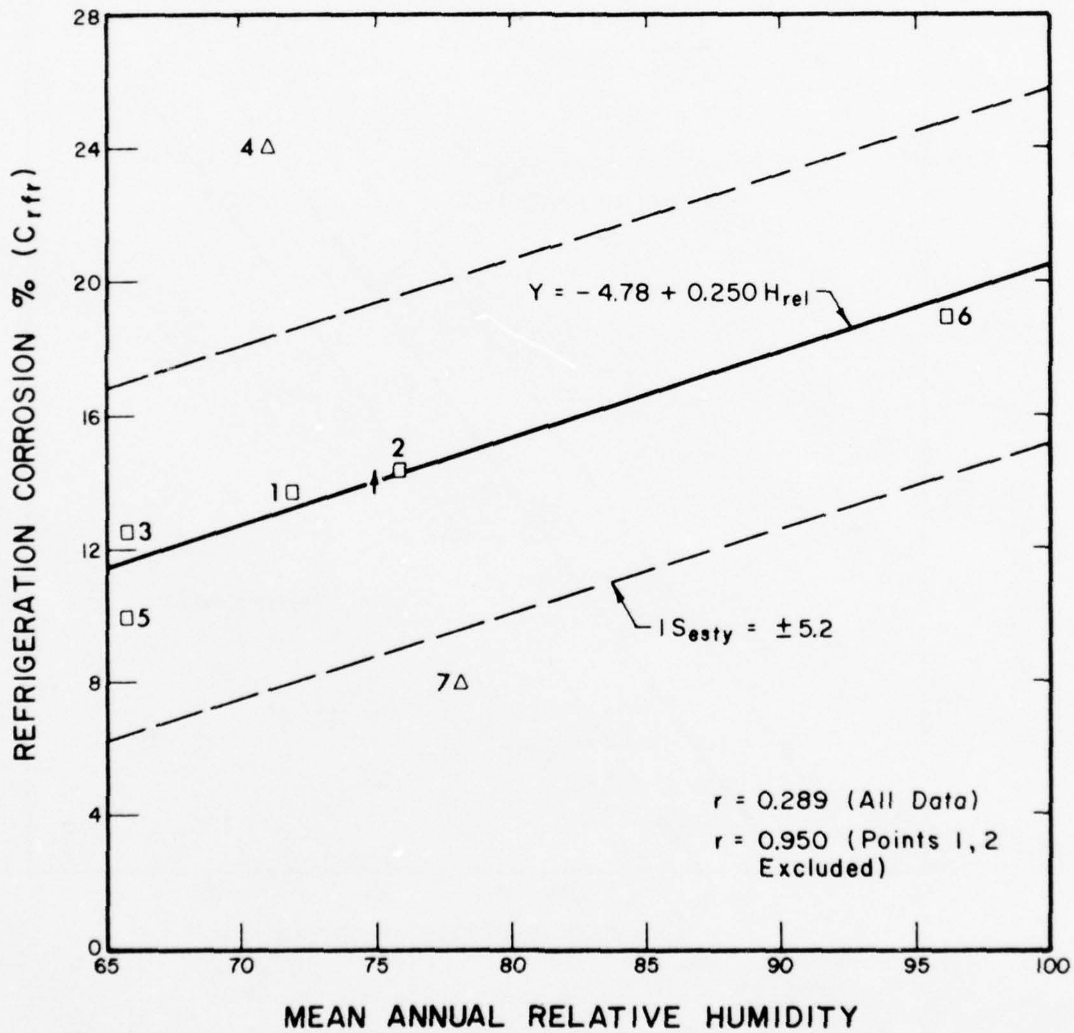

Figure 8. Refrigeration Corrosion Percentage as a Function of Mean Annual Relative Humidity. (Point 7 is Low Due to Minimal Scale Control Since Water is Fairly Soft. Point 4 is High Due to Excess Capacity Required for Other Than Building Cooling Load.)

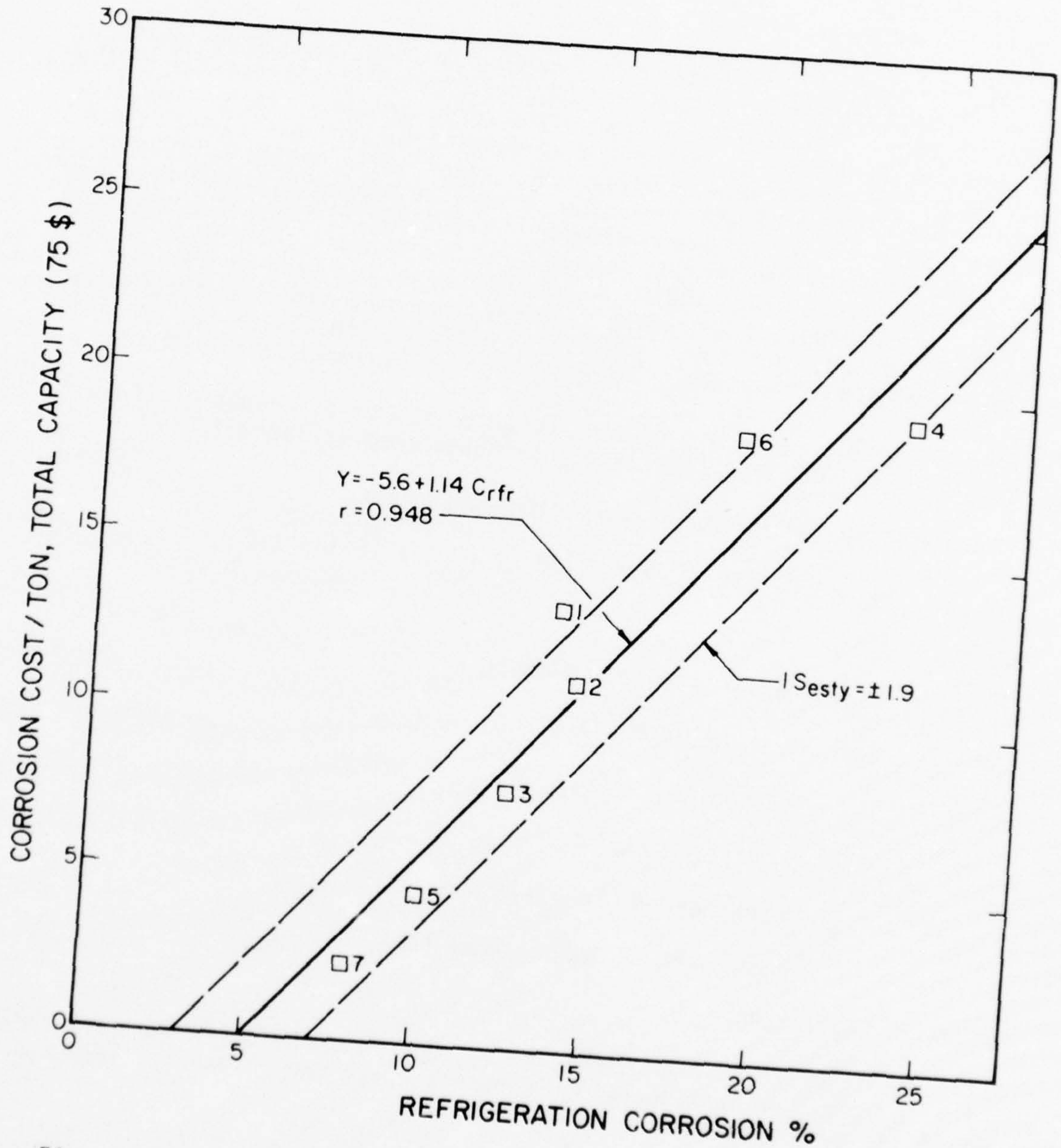

Figure 9. Corrosion Cost per Ton, Predicted From the Refrigeration Corrosion Percentage. (Adjusted for Inflation.)

Prediction equations are:

$$C_{rfr} \pm 5.2 = -4.78 + 0.250\ H_{rel}$$

$$\text{Cost/TON} \pm 1.9 = -5.6 + 1.14\ C_{rfr}$$

EXTERIOR ELECTRICAL

This section is responsible for the maintenance, repair, or replacement of exterior lighting and electrical transmission systems, including airfield lighting for AF bases or Army airfields, if applicable.

Climatic variables considered in attempting to correlate corrosion percentage were relative humidity, temperature, and dew point. Since the bulk of exterior electrical distribution systems were above ground in this study (and for the services in general), they are also exposed to air pollution. Since accumulating sulfur oxides create acidic dew, total sulfur oxide emissions* is a variable. A correlation of the corrosion percentage versus the (relative humidity) x (temperature) product shows promise ($r = 0.856$), although the variance (degree of scatter from the regression line) is substantial. In attempting to optimize corrosion percentage versus dew point, which has good correlation ($r = 0.780$), the percentage deviation from the predicted line was plotted as a function of log ΣSO_x emissions, yielding a Δ %dev/Δ log $\Sigma SO_x \approx 10$. A plot of corrosion percentage versus dew point + 10 log SO_x is shown in Figure 10.

The relationship between corrosion cost per KLF of distribution lines (see Figure 11) is also well correlated, although some variance is noted.

The prediction equations for this work center are:

$$C_{ext} \pm 5.4 = -12.5 + 0.728\ (0.6D_{pt} + 10 \log \Sigma SO_x)$$

where $\Sigma SO_x \geq 1$,

or $C_{ext} \pm 6.1 = -21.3 + 0.00670\ H_{rel}\ T$

and Corrosion cost/KLF $\pm 8.5 = 5.4 + 1.34\ C_{ext}$

where D_{pt} = dew point, °F

ΣSO_x = tons/year/km^2

H_{rel} = mean annual relative humidity

T = mean annual temperature (°F)

INTERIOR ELECTRICAL

All activities related to maintenance, repair, or installation of interior electrical systems, or instruments or controls which are primarily electrical, are within the jurisdiction of this work center.

*Total sulfur oxide emissions (ΣSO_x).

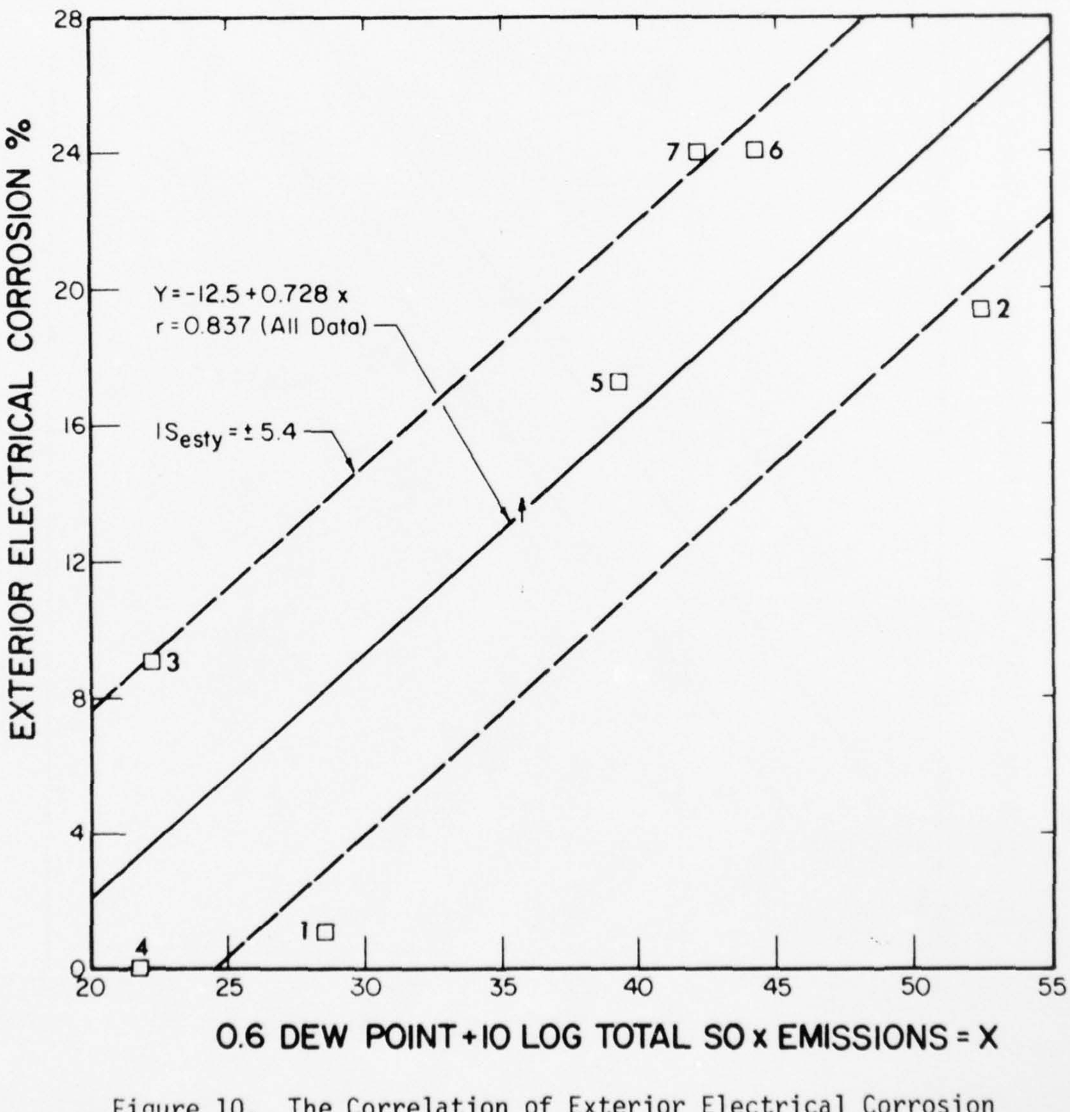

Figure 10. The Correlation of Exterior Electrical Corrosion Percentage as a Function of Dew Point and Annual Cumulative Sulfur Oxide Emissions, in Tons/Yr/km^2.

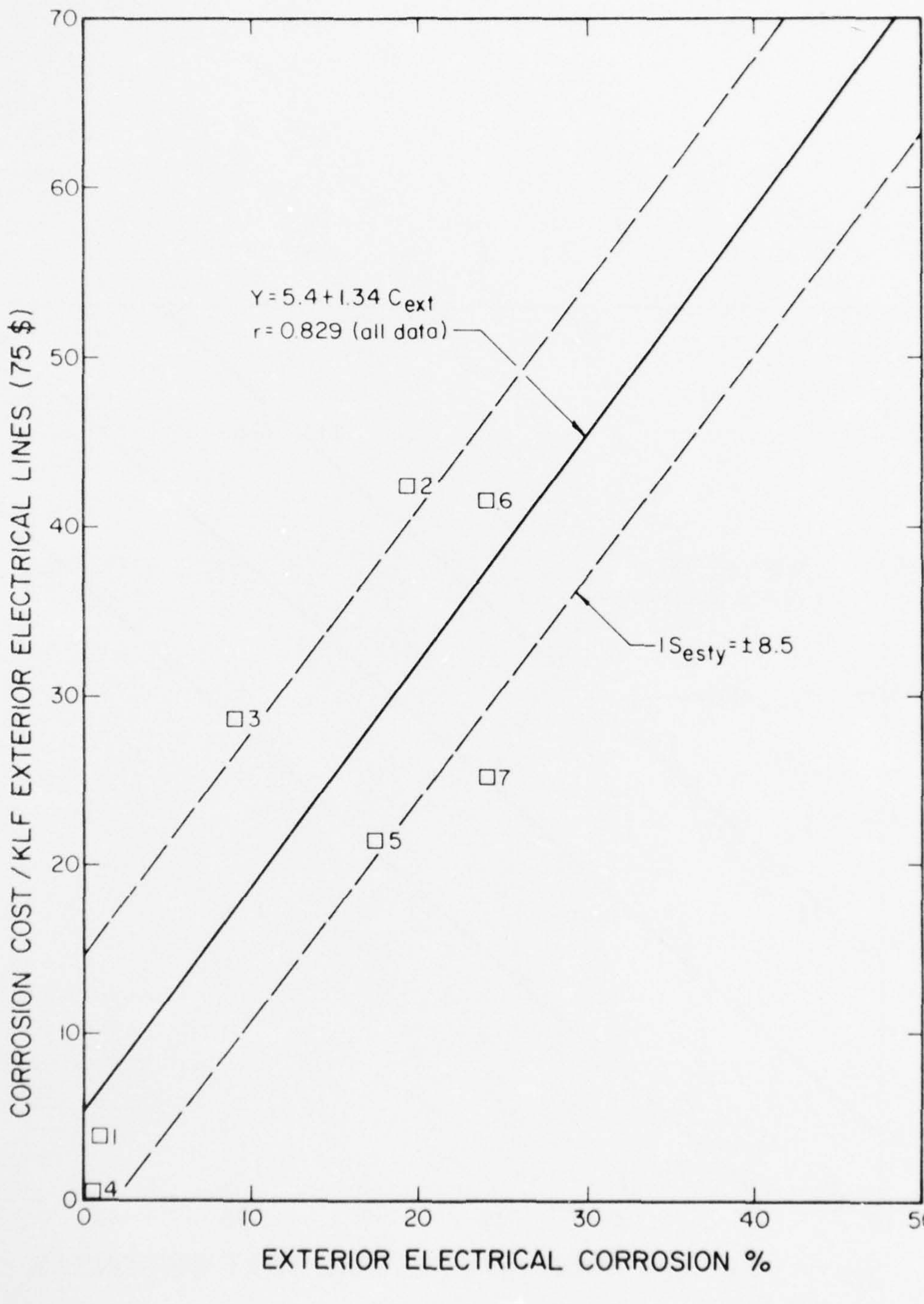

Figure 11. The Corrosion Cost per Thousand Linear Feet of Exterior Electrical Lines as a Function of the Exterior Electrical Corrosion Percentage. (Adjusted for Inflation.)

Since most buildings have controlled temperatures, outside fluctuations are not critical to most interior electrical systems. Rainfall may seep through conduits or other points into a structure, but this is exceptional. This leaves relative humidity as the remaining predictor variable, since not all buildings are under humidity control (such as computer rooms).

Figure 12 correlates interior electric corrosion percentage (C_{int}) with relative humidity. The correlation coefficient is strongly linear ($r = 0.934$) and variance is reasonably small.

Since the interior electrical function deals with such diverse systems, total building area was selected as the unit dimension. The corrosion cost/ΣKSF of total installation building surface as a function of (corrosion percentage)$^{1/2}$ is well correlated, as noted in Figure 13.

Summarizing predictor equations,

$$C_{int} \pm 3.4 = -54.7 + 0.835\, H_{rel}$$

and Corrosion cost/ΣKSF total building surface = $1.38 \sqrt{C_{int}}$

STRUCTURES MAINTENANCE/MASONRY (CARPENTRY)

The functions of these AF work centers are combined into one section in the Army Facility Engineer organization. Primary responsibilities are the maintenance, repair, and improvement of wooden or masonry buildings and structures. Typical components maintained are roofing, plastering, floor covering, and screening. Although most of the work these personnel perform involves nonmetallics, often damage results from failure of metallic components, such as rain leaks from a metal roof or water damage from corroded overhead piping systems.

Several climatic variables were considered as predictor elements, including annual rainfall, relative humidity, and mean ambient temperature. Various combinations of these potential variables in product or additive form were correlated with carpentry corrosion percentage; rainfall + temperature yielded the best results. This correlation is plotted in Figure 14.

The corrosion cost per sum total KSF of installation building surface is plotted as a function of carpentry corrosion percentage in Figure 15. Since both scatter and variance are severe, this prediction equation must be used with caution.

In summary, prediction equations for the structures maintenance - masonry functions (carpentry) are as follows:

$$C_{carpm} \pm 7.2 = -47.7 + 0.571\,(R + T)$$

and Corrosion cost/ΣKSF total bldgs = $2.4 + 0.643\, C_{carpm}$

PROTECTIVE COATING (PAINTING)

This work center is responsible for all types of coating applications (primarily interior and exterior paint) and the manufacture of signs.

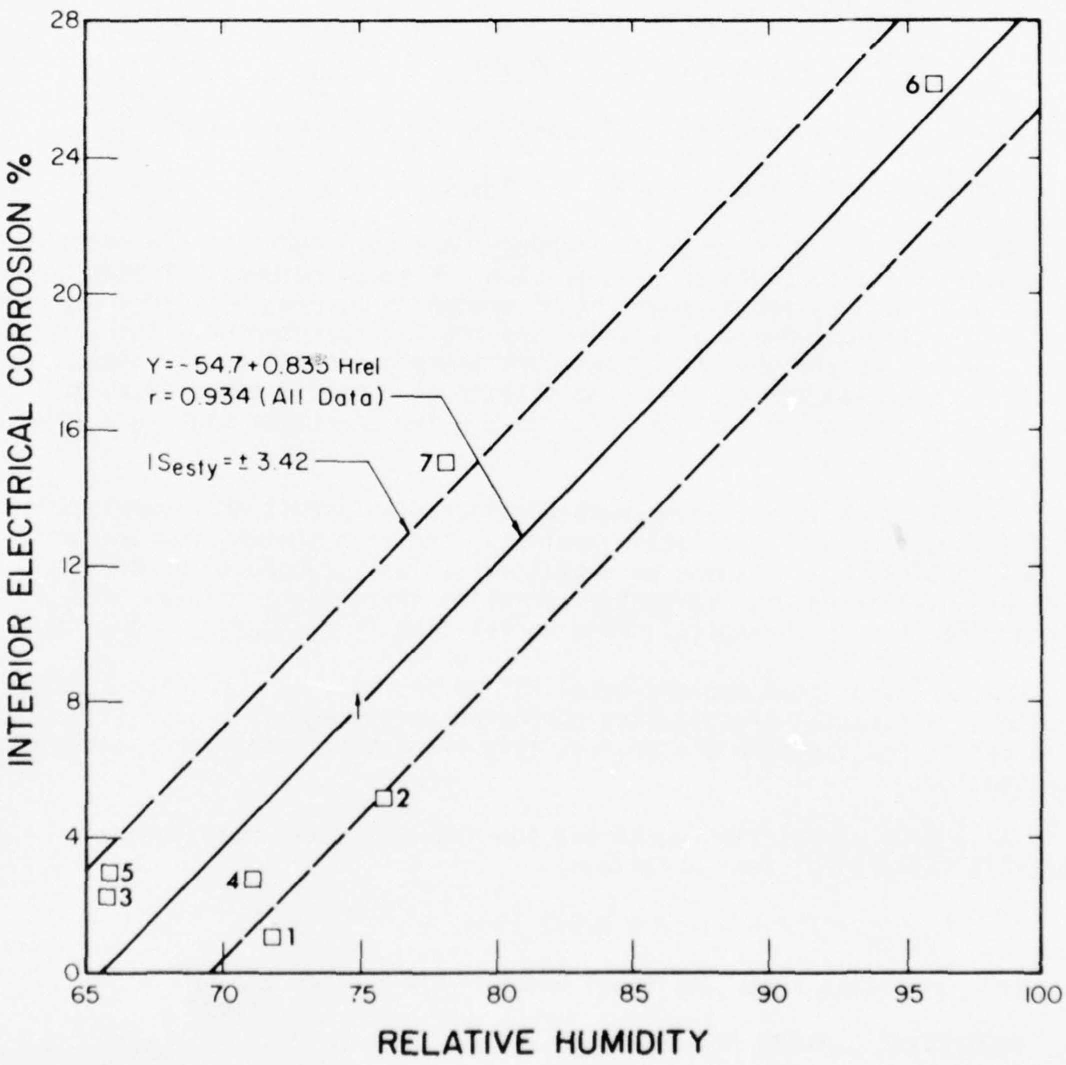

Figure 12. The Interior Electrical Corrosion Percentage as a Function of Mean Annual Relative Humidity.

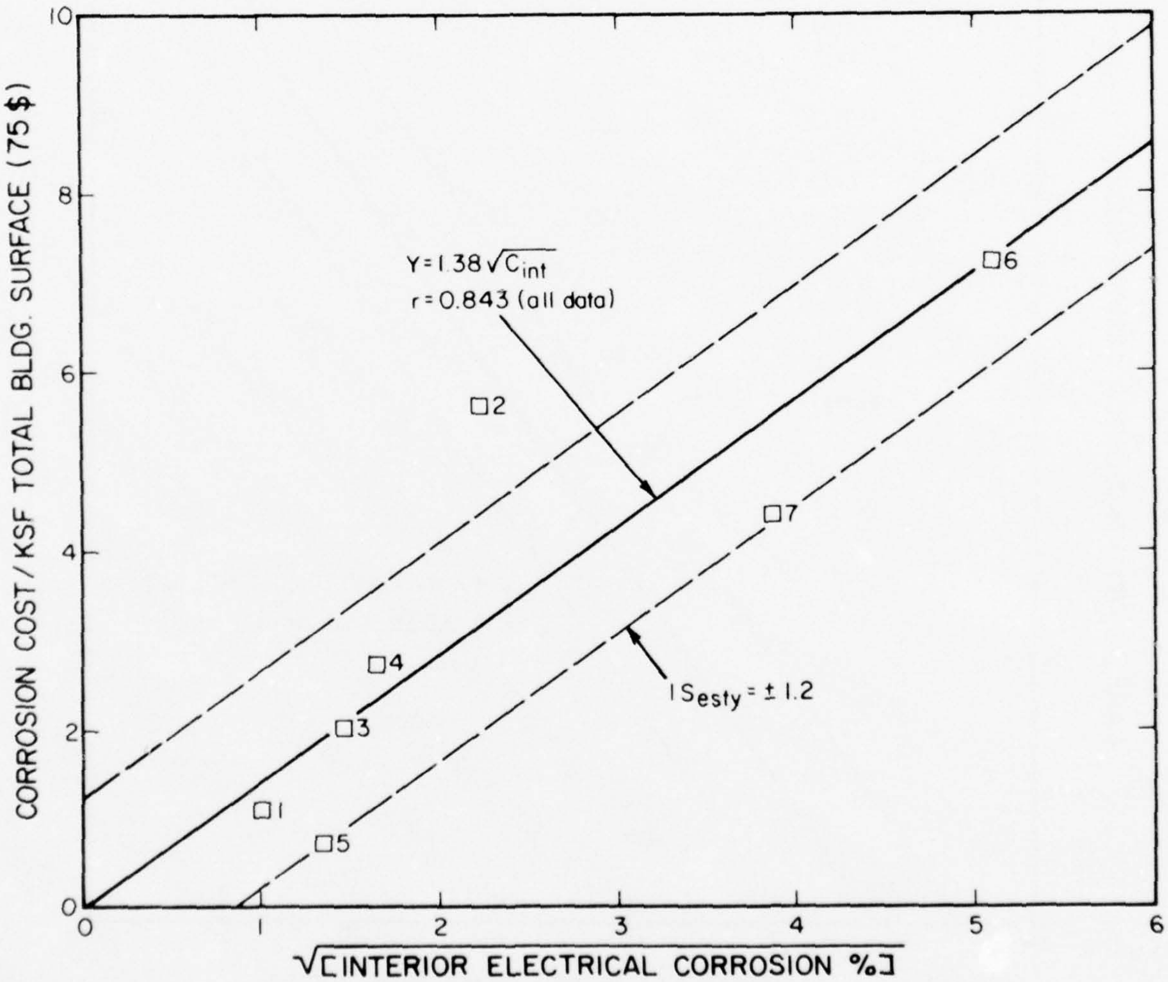

Figure 13. The Corrosion Cost per Thousand Square Feet of Building Surface as a Function of the Square Root of the Interior Electric Corrosion Percentage. (Adjusted for Inflation.)

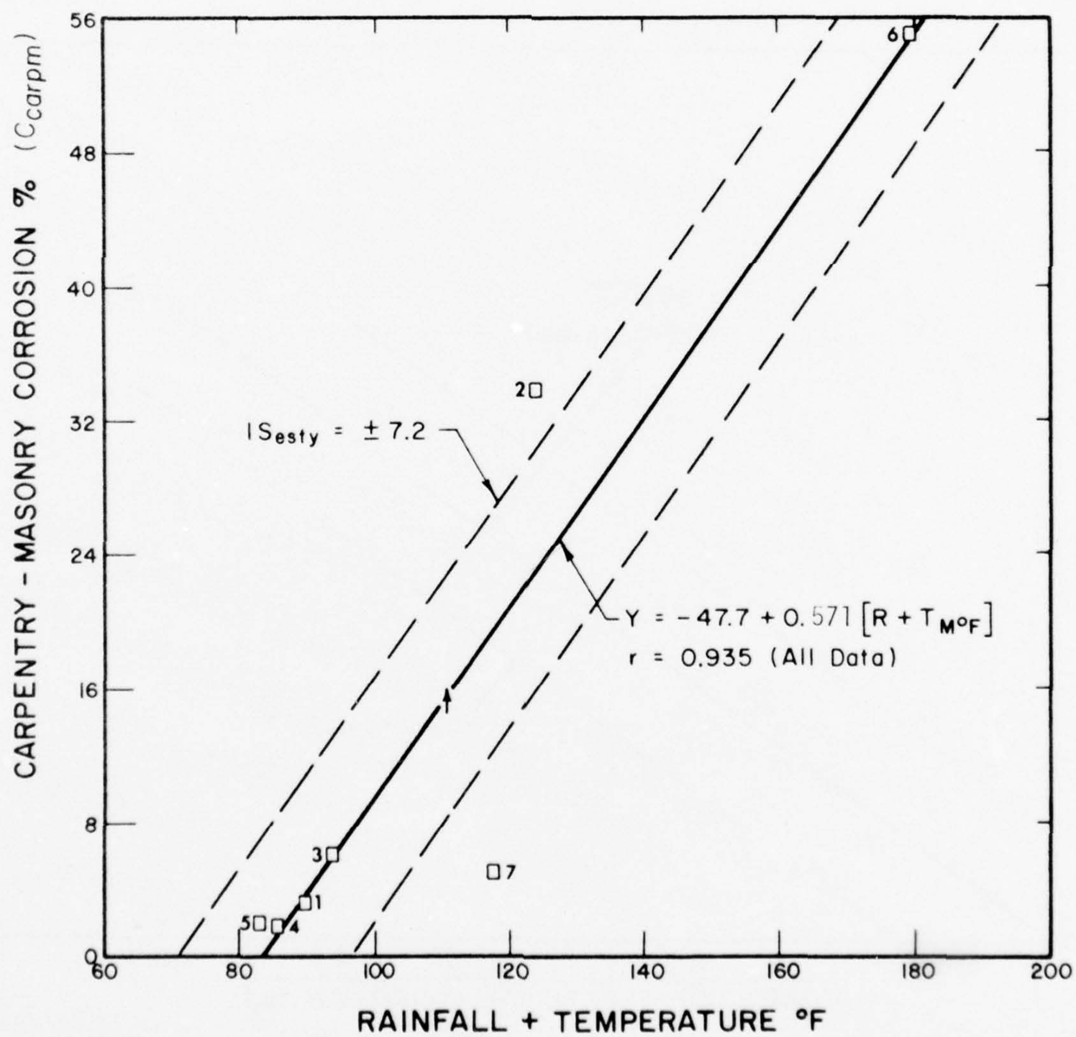

Figure 14. The Carpentry-Masonry Corrosion Percentage as a *Function of Annual* Precipitation (in Inches) and Mean Annual Temperature (°F).

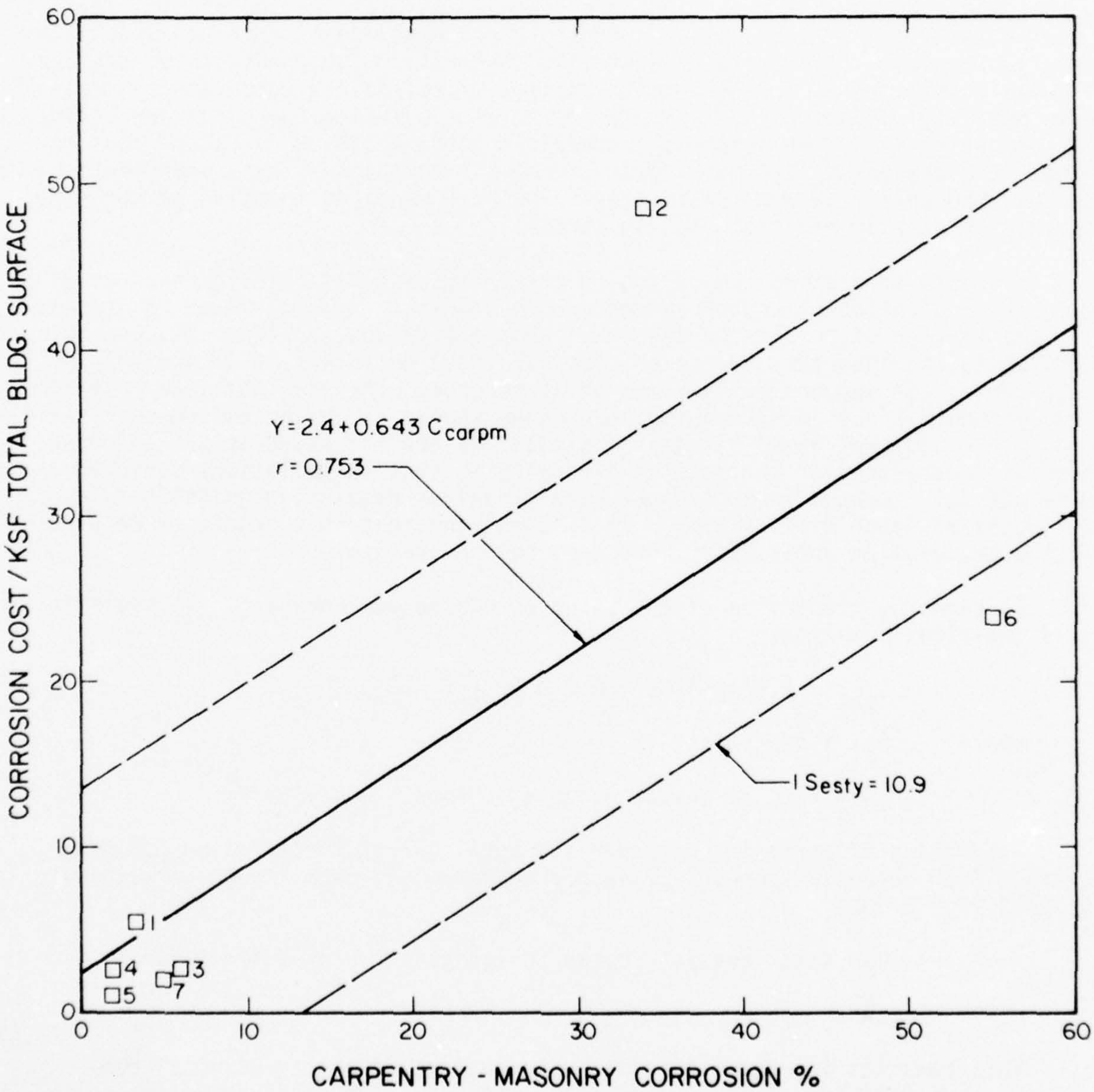

Figure 15. The Corrosion Cost per Thousand Square Feet of Building Surface as a Function of Carpentry and Masonry Corrosion Percentage. (Adjusted for Inflation.)

Any expenditure of resources toward exterior painting was considered as corrosion-related; this excluded military family housing, which is usually handled by contractor personnel. Most of the structures requiring repainting had exterior metal skins and roofs, although masonry walls or gypsum board sustaining corrosion-induced damage necessitating painting were also included.

Relevant variables which affect the deterioration of paint on metal, including rainfall, dew point, temperature, relative humidity, and air pollutants, were correlated against corrosion percentages. Rainfall may puddle in crevices, causing localized attack. A sufficiently high temperature, combined with high relative humidity, can degrade paint film integrity. The corrosion percentage is well correlated ($r = 0.845$) as a function of rainfall x temperature x relative humidity. However, the correlation between painting corrosion percentage and dew point + ΣSO_x emissions is remarkably good, as shown in Figure 16. The higher the dew point, the more moisture the air contains. Thus, when dew condenses, the sulfur oxides combine to form acidic media destructive to both the organic paint film and the metal substrate.

However, predicting the corrosion cost/ΣKSF of total building surface as a function of paint corrosion percentage is somewhat disappointing. By observing the cluster of points for the lower abscissa values in Figure 17, one is tempted to conclude that corrosion cost/KSF total buildings is a constant in this range, and exponentially rises at 16 percent. The straight line relationship is drawn since an increasing percentage should imply increasing cost/building, since manpower levels in painting sections are increased as ΣSF increases. A possible explanation for lack of linearity is that installations surveyed were not fully manned in accordance with manual or regulation guidelines, due to localized labor difficulties. It is concluded that this predictor be used with extra caution until sufficient data become available.

In summary, prediction of the paint corrosion percentage (C_{pnt}) satisfies this empirical equation:

$$C_{pnt} \pm 1.4 = -9.36 + 0.279\,(D_{pt} + \Sigma SO_x)$$

where D_{pt} = dew point, °F

ΣSO_x = total sulfur oxide emissions, tons/year/km^2

Prediction of corrosion cost per sum total KSF of installation building surface from corrosion percentage is <u>not</u> recommended, even though correlation is good ($r = 0.808$):

$$\text{Corrosion cost/KSF total buildings} \pm 1.6 = -0.4 + 0.386\,C_{pnt}$$

METAL WORKING

This function is responsible for maintenance and repair of metal components on facilities, including welding. The manufacture, repair, and installation of sheet metal products also account for a major portion of work.

The variables which affect the corrosion rate of both interior and exterior metal components (mostly plain carbon steels, high-strength low-alloy steels,

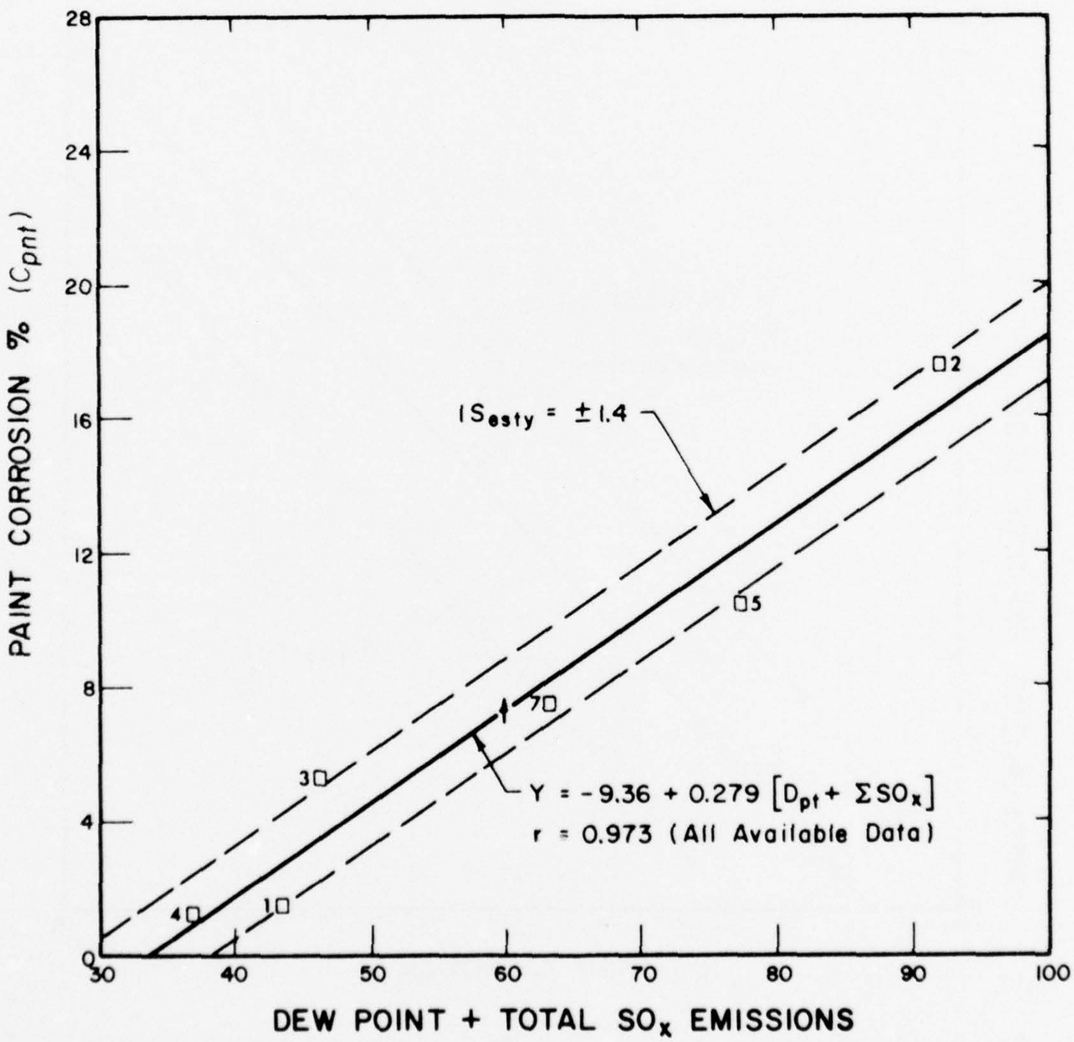

Figure 16. Paint Corrosion Percentage as a Function of Dew Point (°F) + Cumulative SO_x Emissions (Tons/Yr/km^2).

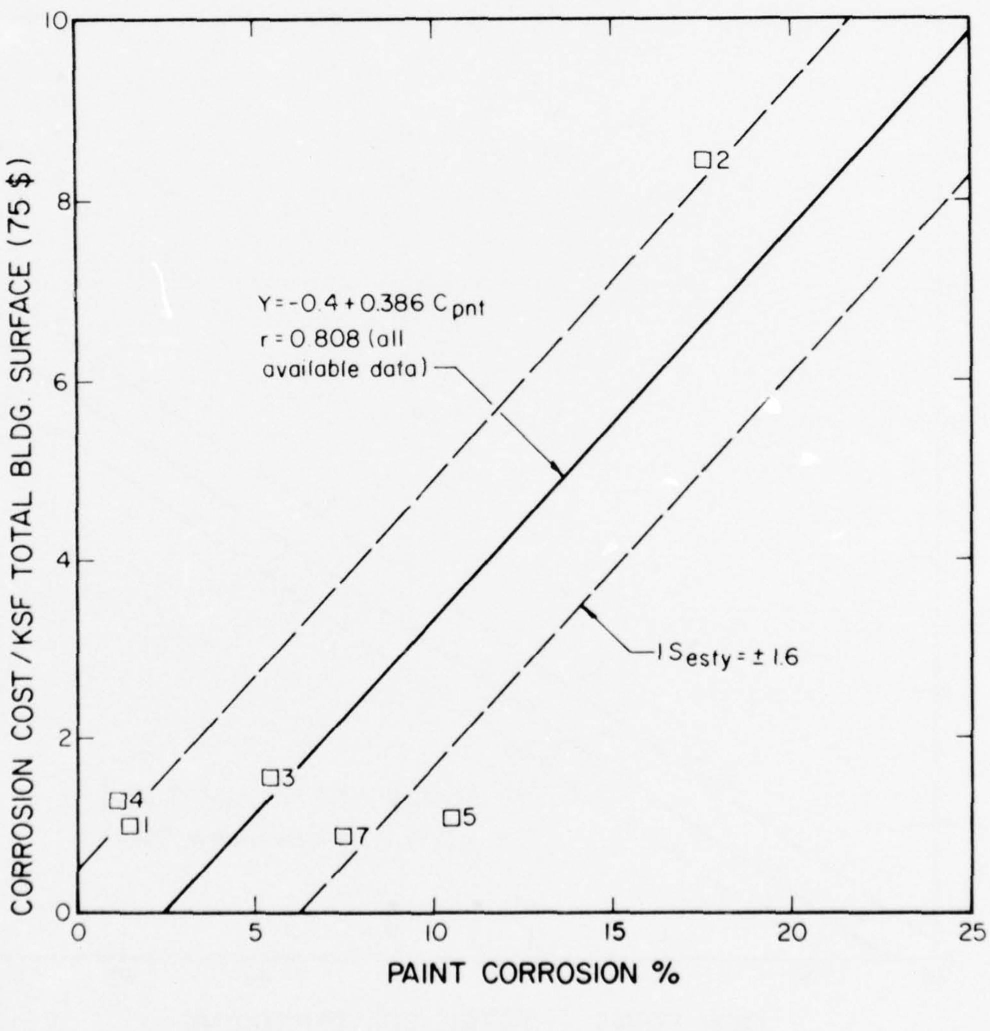

Figure 17. The Corrosion Cost per Thousand Square Feet of Building Surface as a Function of the Paint Corrosion Percentage. (Adjusted for Inflation.)

and galvanized sheet steels) are temperature, relative humidity, rainfall, dew point, and air pollutants. The product of relative humidity x temperature has fairly low correlation ($r = 0.360$) with corrosion percentage, although dew point was a better single predictor element ($r = 0.644$). Optimized with ΣSO_x emissions (which accumulate on the metal surface with time), the correlation was improved and variance minimized, as noted in Figure 18. However, it appears that ΣSO_x emissions are influential only at output levels $\geq$ 10 tons/year/km².

An equally good correlation was obtained for corrosion cost/ΣKSF total installation building surface as a function of the metal working corrosion percentage (C_{mtlw}), as shown in Figure 19.

In summary, prediction equations are as follows:

$$C_{mtlw} \pm 3.8 = 2.13 + 0.212[D_{pt} + 10 \log SO_x]$$

where $\Sigma SO_x \geq 10$ tons/year/km²,

and Corrosion cost/KSF total bldgs $\pm$ 2.4 = C_{mtlw}

WATER AND WASTE

These activities are concerned with the O&M, repair, and installation of water supply equipment and processing systems, including the processing of sewage and industrial wastes.

Because of the diversity of the systems maintained by Water and Waste personnel*, no one variable (nor combinations of the logical variables) seemed to sharply correlate with corrosion percentage (C_{ww}). Variables considered were relative humidity, dew point, and temperature, all of which influence the corrosion rate of above-ground structures. Water supply conductivity, total dissolved solids, or even Langelier Index may also be effective elements, although these data are not readily available in standard reports.

Relative humidity alone had the best correlation of all the variables mentioned ($r = 0.787$), as noted in Figure 20, when employed to predict corrosion percentage. The functional relationship between corrosion cost/KGAL produced was good ($r = 0.868$) as shown in Figure 21.

Summarizing cost prediction equations,

$$C_{ww} \pm 2.4 = -37.6 + 0.615\ H_{rel}$$

and corrosion cost/KGAL produced $\pm$ 0.002 = $0.00503C_{ww}$.

LIQUID FUELS

This work center is usually associated with AF bases because of extensive refueling requirements for aircraft, although Army airfields, primarily for

*The Army splits this function into three groupings: (1) water plant, (2) sewage plant, and (3) exterior water and sewer maintenance (if installation is large enough).

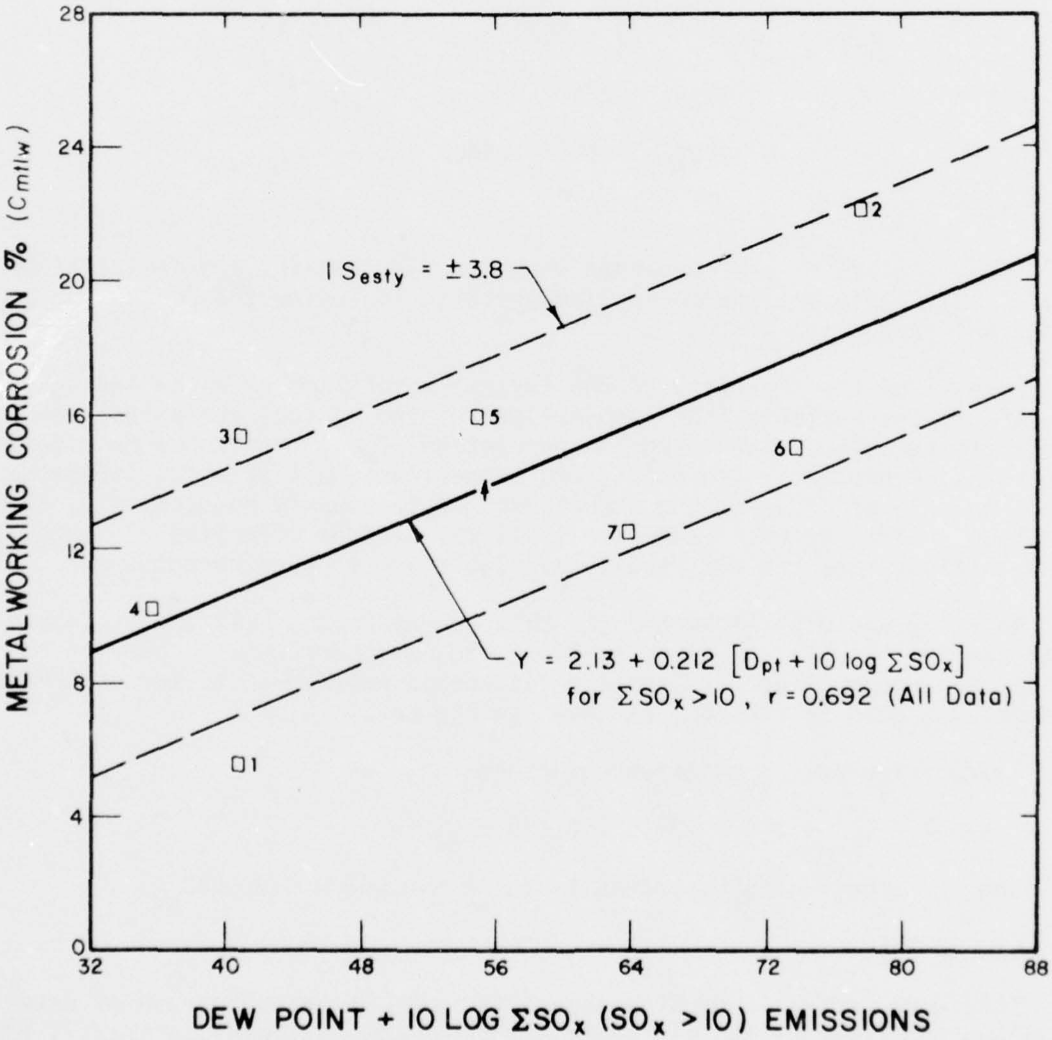

Figure 18. Metalworking Corrosion Percentage Predicted as a Function of Dew Point (°F) + 10 Log Cumulative SO_x Emissions (Tons/Yr/km^2).

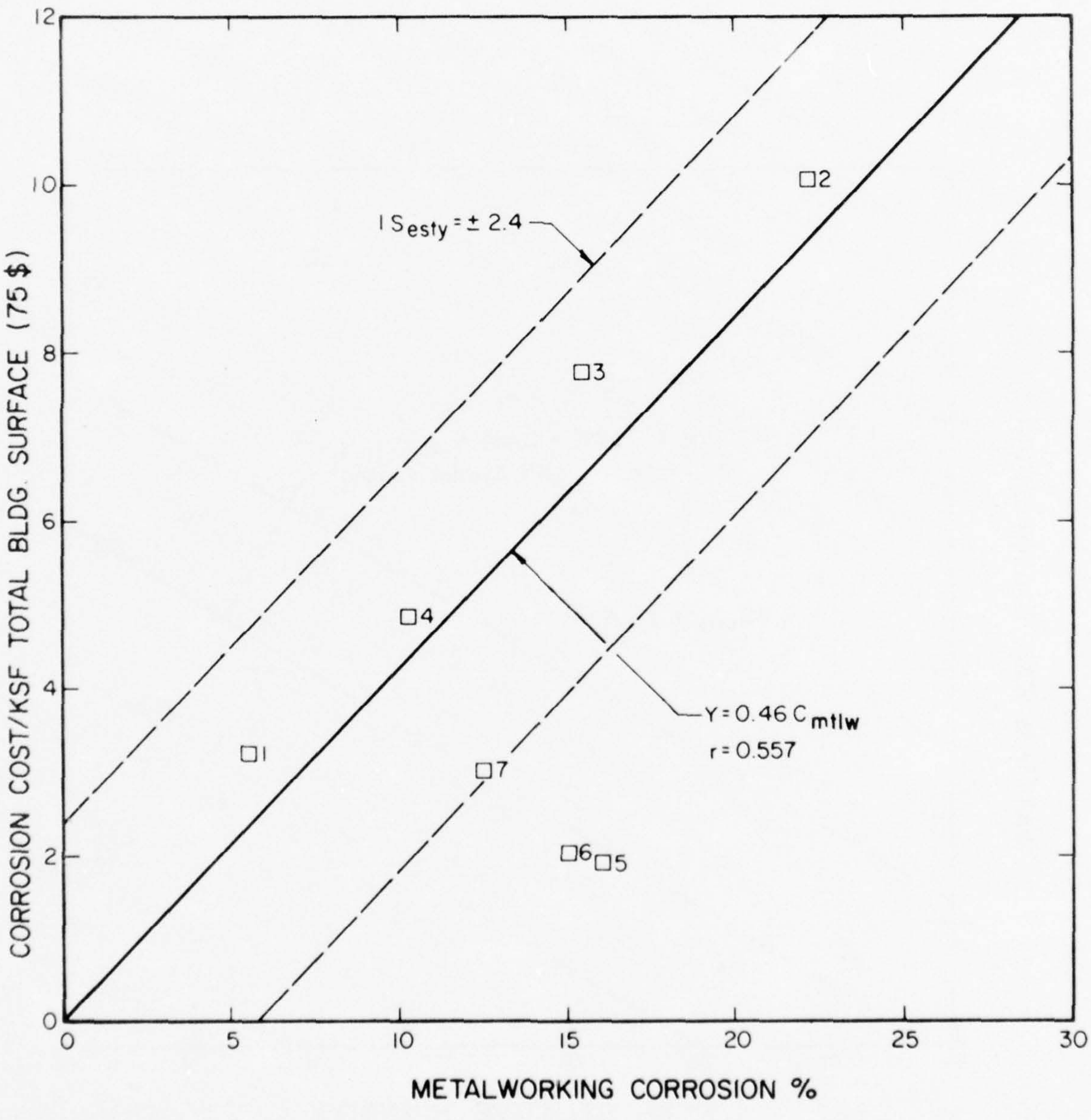

Figure 19. The Corrosion Cost per Thousand Square Feet of Building Surface as a Function of the Metal-Working Corrosion Percentage. (Adjusted for Inflation.)

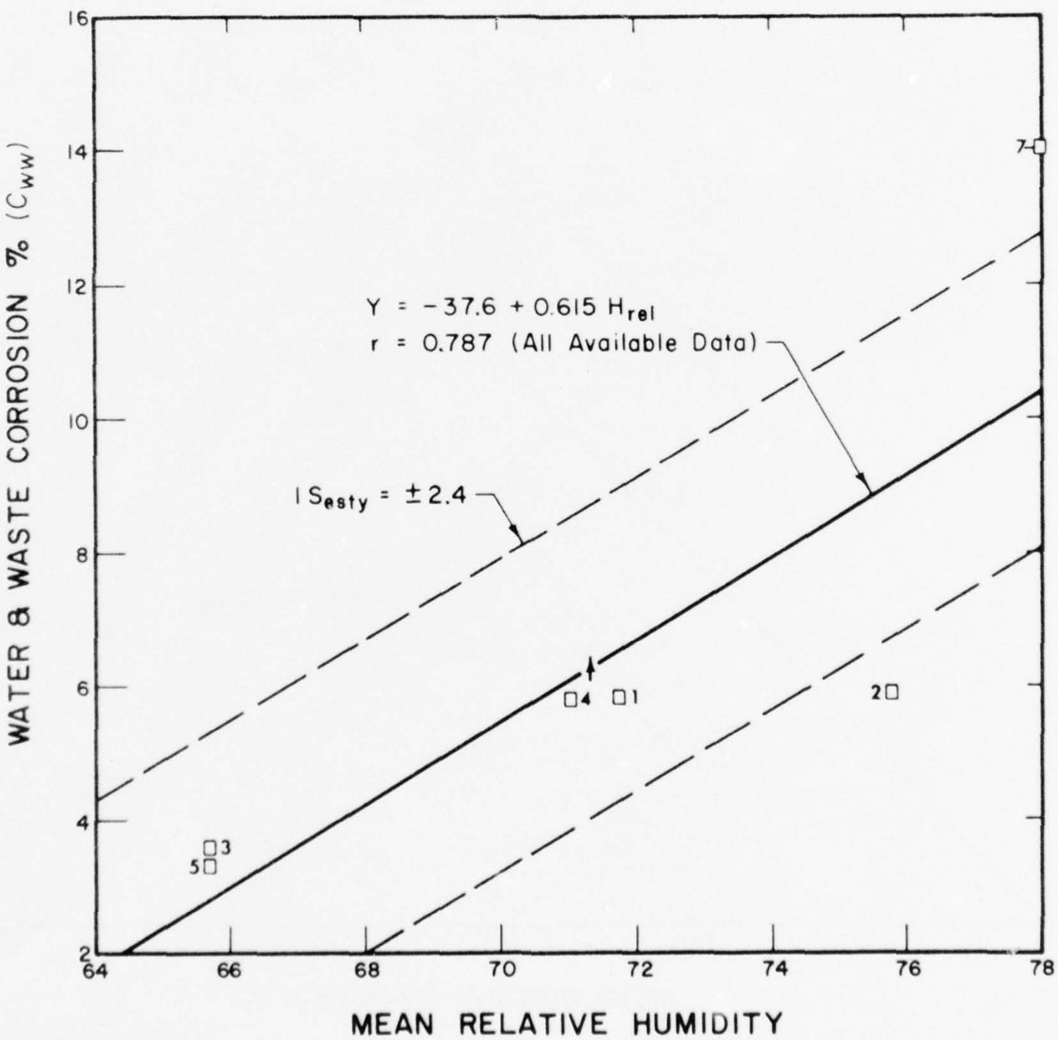

Figure 20. The Water and Waste Corrosion Percentage (C_{WW}) as a Function of Mean Annual Relative Humidity.

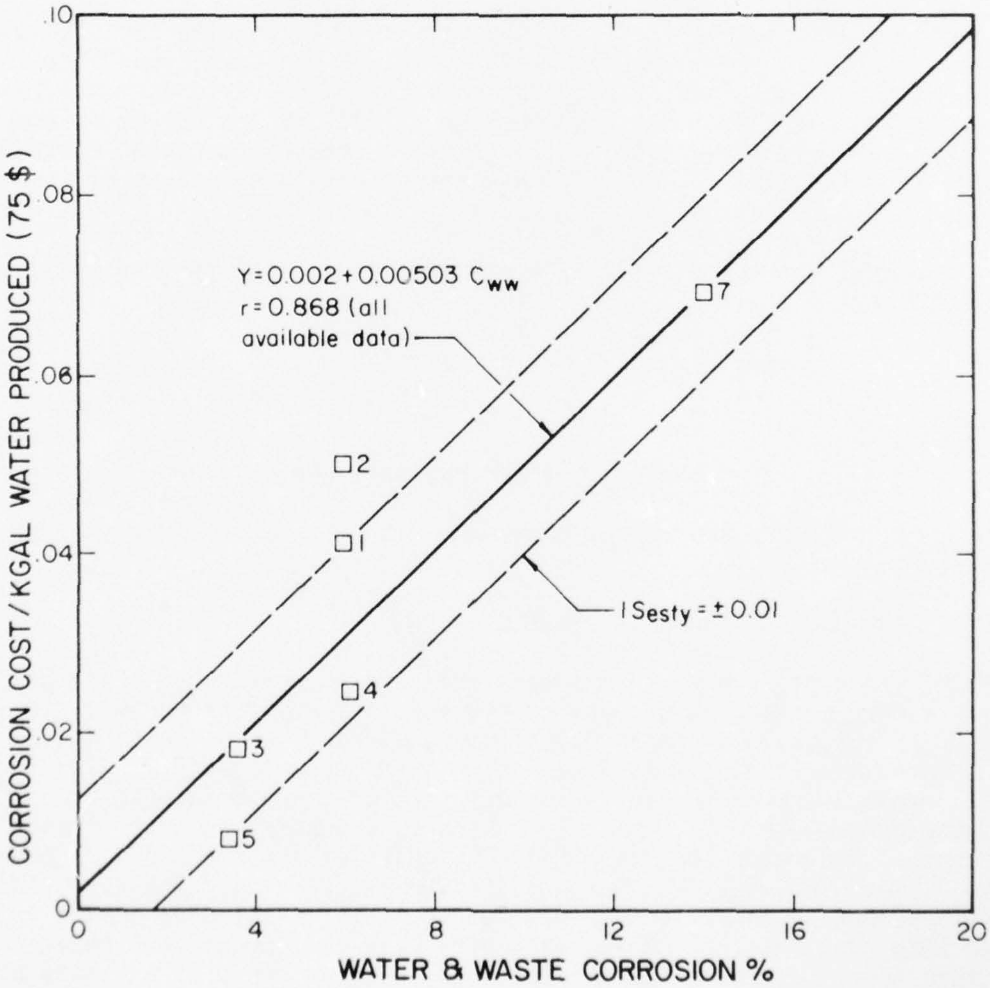

Figure 21. Corrosion Cost per Thousand Gallons of Water Produced as a Function of the Water and Waste Corrosion Percentage. (Adjusted for Inflation.)

helicopters, may have extensive liquid fuel distribution networks. The Army equivalent section is designated Fuel Storage and Issue. Army installations surveyed had minimal fuel storage capacity.

Liquid fuel facilities consist primarily of underground refueling distribution piping, and above-ground and underground storage tanks. Logically, the variables affecting liquid refueling facilities would be dew point, since dew condenses on or inside storage tanks, and soil resistivity, which influences the extent of attack on underground piping and tanks. Corrosion percentage should be directly related to dew point and inversely related to soil resistivity. When corrosion percentage was plotted as a function of dew point-soil resistivity, a virtual straight line resulted, ignoring one anomalous point. Due to survey sampling time of only two months, an abnormally high percentage resulted at this installation, since a substantial portion of time was devoted to repairing extensive damage (corrosion-induced leakage) caused by an explosion. See Figure 22 for this plot.

To accommodate such variations, the mean is not shown on the straight line drawn, which is the expected normal curve. A positive error line is drawn about the normal line, taking the anomalous point into account. Since the correlation for this line is perfect ($r = 1.00$), there can be no error, which is an unlikely situation. No correlation between corrosion cost/KBBL dispensed as a function of corrosive percentage resulted because of insufficient data for correlation.

In summary, corrosion percentage for the liquid fuel systems (C_{lf}) can be predicted by:

$$C_{lf} = 92.8 \left(\frac{D_{pt}}{\text{ohm-cm}_{min}}\right)$$

where D_{pt} = dew point, °F.

ohm-cm_{min} = minimum soil resistivity

Insufficient data are available to warrant prediction of system corrosion cost at this time.

OTHER NON-CORRELATING WORK CENTERS

Power Production work centers were analyzed at only three AF bases. No comparable Army section is present in the Facility Engineer organization, although Organizational Maintenance performs similar work on diesel engines. Since maintenance schedules take corrosion into account, such as flushing of coolant, replacement of manifolds and muffler, pitting of injector tips, and so on, the percentage will be fairly constant, depending on what flexibility the Technical Order (or Technical Manual) schedules are accorded. Percentages were 16.7, 16.9, and 5.2, and were related to KW capacity. The corrosion Cost/KW appeared to be related to dew point. This correlation should be treated with caution since data are scanty. The cost prediction equation was determined to be Cost/KW = $-36.3 + 1.1. D_{pt}$, with an error of estimate of ± 4.7. This equation is only valid for $D_{pt} > 33$°F.

The Pavements and Grounds function is present in both AF and Army facility maintenance organizations, and encompasses essentially identical jurisdictions

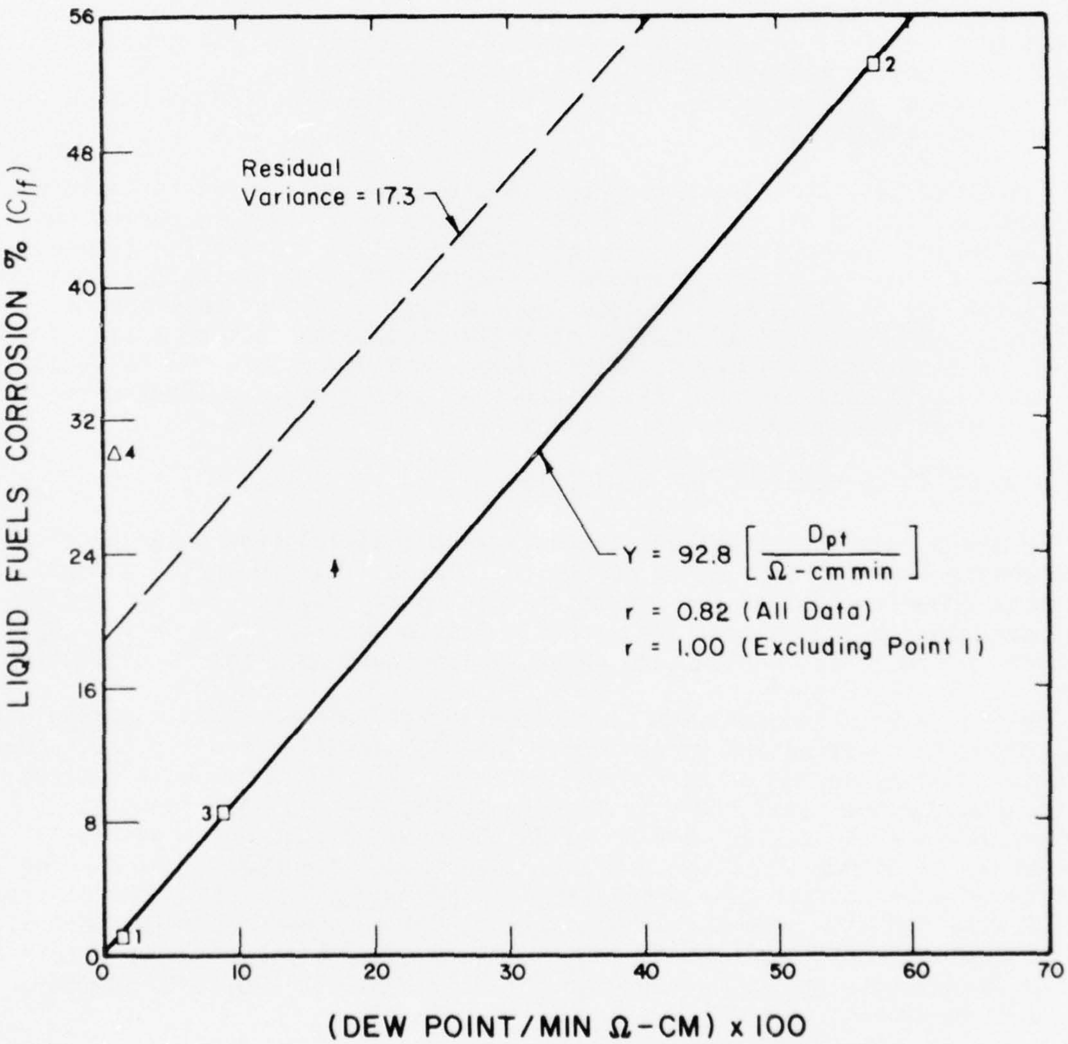

Figure 22. Correlation of Liquid Fuels Corrosion Percentage Vs Dew Point/ Minimum Soil Resistivity (°F/ohm-cm.) (Correlation Coefficient Including Anomalous Point is 0.821. When Point is Dropped, Unbiased Residual Variance About the Regression Line Instead of the Mean Is Employed.)

of equipment maintenance, grounds upkeep, railroads, and concrete or asphalt paving work. These work centers perform work indirectly related to corrosion, such as the restoration of an excavation site after a corrosion-induced leak was repaired.

However, the Pavements function was not chosen as a cost predictor element because of the high variability of its percentages, many of which are small enough to be considered negligible. No correlation was found with the percentages of other work centers that would be the sources of their corrosion work, such as plumbing or heating systems.

The causes of this non-correlation are multiple. The assigned tasks vary as a function of installation mission and topography. If the installation is located in a snowfall area, much snow removal equipment will be deployed. If there are extensive training areas, the Grounds or Forestry sections may be dominant. If no airfields are present, the Pavements function will be confined to base roads and markings.

There may be a time lag before the area that was excavated is restored. For example, torn-up highway asphalt may not have been replaced during the sampling period, although the trench was backfilled to let traffic proceed. Similarly, a lawn may not be reseeded or sodded until a later date, since the work center may be occupied with other non-corrosion-related commitments. The sampling procedure in the AF studies of taking two months out of a fiscal year (usually not consecutive) may have introduced some error into the calculations. This was done to take seasonal fluctuations into account, and limited the massive number of work documents to be examined.

CORROSION COSTS OF CONSTRUCTION CONTRACTS

In the surveys construction contracts were analyzed over a period of years to determine what percentage was corrosion related. Maintenance and repair contracts comprise most of the corrosion-related contracts. The percentages were determined by adding all the corrosion costs over the time period analyzed, and dividing by total construction value (values were adjusted for inflation).

In Figure 23, the corrosion percentage for all O&M work was compared with this composite construction percentage. The O&M overall corrosion percentage was determined by adding up corrosion costs for all applicable work centers, and dividing by the total costs (excluding fuels) for all work centers. Scatter occurs when backlog work normally performed by O&M work centers is intended to be accomplished by contract. Construction projects may also be deferred because of lack of authorization or appropriation. This correlation must be regarded with some degree of caution, since it represents a construction corrosion average percentage *over the long run* (>3 years). The nature and size of maintenance and repair and MCP (or MCA) projects fluctuate severely from year to year.

A safer means of estimating whether base projects are corrosion related is to simply inspect the DD Form 1391 Military Construction Project data or other supportive project justifications and determine a corrosion percentage or cost for that fiscal year.

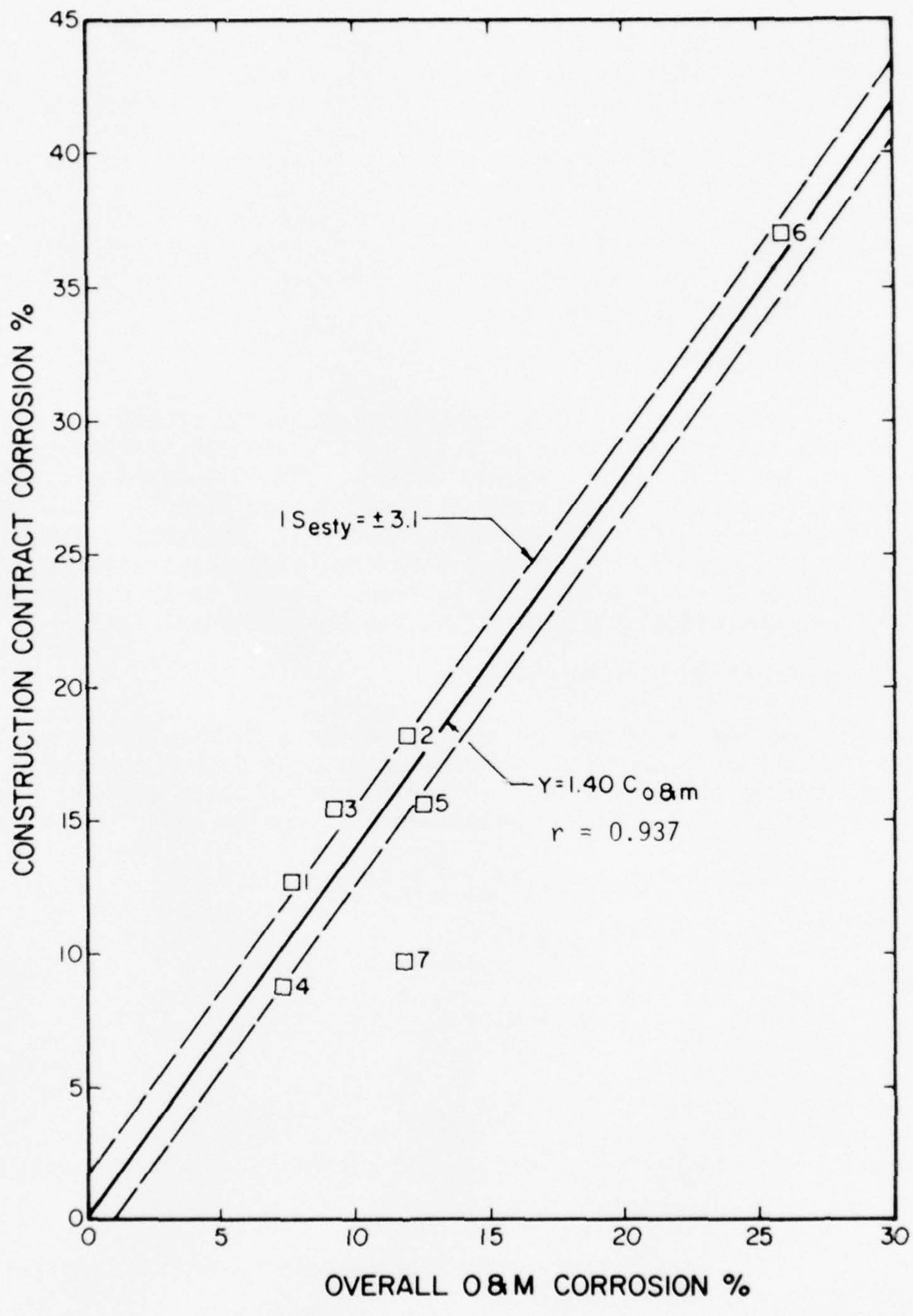

Figure 23. The Construction Contract Corrosion Percentage Predicted from the Operations and Maintenance (O&M) Corrosion Percentage. (Overall O&M Percentage Is Obtained by Adding all Corrosion-Related O&M Costs and Dividing by Total O&M Expenditures Excluding Fuels.)

CORROSION-INDUCED ENERGY LOSSES

Other direct corrosion costs are the loss of fluids and gases which are energy sources or which consume energy in their production. These media may leak out of pressurized piping, or seep from above- or belowground tanks.

Not included in this category are heat transfer processes which become less efficient due to scale formation caused by lack of proper chemical additives or inattention to established procedure. The largest sources of this inefficiency are boiler tube scale and fouling on refrigerant condenser/evaporator coils. These indirect degradations are not considered here, but will be treated in a separate report.

THE GENERALIZED CORROSION COST MODEL

Facility corrosion costs can be predicted by one of two methods. The first method, designated as the work center calculation, necessitates a knowledge of the labor, material, and equipment costs associated with predictor work centers or sections. Work center costs may be directly known or approximated from manning guides (References 23 and 24). The second method, designated the system calculation, requires data regarding actual dimensions and capacities of corrosion-cost prediction systems. Common to both methods are requirements for various climatic, geographic, and environmental data.

COST CALCULATION BY WORK CENTER

In this method, a corrosion percentage for a particular work center is derived from commonly available prediction data, and then applied against the total work center cost. All work center corrosion costs are summated, resulting in an installation facility maintenance corrosion cost. Mathematically,

$$C_{i\%} = f_a(V_c) + f_b(V_g) + f_c(V_e) \text{ for } i = 1\text{-}11$$

and

$$W_i = C_{\%i}\ (\Sigma T_{wci})$$

$$W_{total} = \sum_{1}^{n} (W_1 + W_2 + W_3 \ldots W_n)$$

$$\Sigma \text{ corrosion cost} = W_{total} + E + C_{cost}$$

where V_c, V_g and V_e = designated climatic, geographic and environmental variables

$C_{i\%}$ = corrosion percentage associated with a specific work center

C_{cost} = corrosion related construction costs

23 Army Pamphlet 570-551, *Staffing Guide for Army Garrisons*, January 1972, pp 2-324 to 2-373.

24 AF Manual 26-3, *Manpower Standards, Vol 4, Direct Support*, 2 February 1973.

W_{total}, W_i = work center corrosion cost, all work centers or individual

ΣT_{wci} = total work center cost (labor, materials, equipment)

E = energy losses, mostly from pressurized systems

The complete equation is as follows:

$$W_{total} = (\Sigma \text{ plumbing costs})\ (44.3 - 0.00908\ (\Omega\text{-cm}))/100 +$$
$$(\Sigma \text{ heating systems costs } (53.0 + 0.000799\ \text{MBtu}/T_{mF} - 0.642\ T_{mF})/100$$
$$(\Sigma \text{ refrigeration costs})\ (-4.78 + 0.250\ H_{rel})/100 +$$
$$(\Sigma \text{ ext electric costs})\ (-12.5 + 0.727\ (0.6D_{pt} + 10 \log \Sigma SO_x))/100 +$$
$$(\Sigma \text{ carpentry costs})(-47.7 + 0.571\ (R_F + T_{m°F}))/100 +$$
$$(\Sigma \text{ painting costs})\ (-9.36 + 0.279\ (D_{pt} + \Sigma SO_x)/100 +$$
$$(\Sigma \text{ metalworking costs})\ (2.13 + 0.212\ (D_{pt} + 10 \log \Sigma_1\ 50_x))/100 +$$
$$(\Sigma \text{ interior electric costs})\ (-54.7 + 0.835\ H_{rel})/100 +$$
$$(\Sigma \text{ water and waste costs})\ (-37.6 + 0.615\ H_{rel})/100 +$$
$$(\Sigma \text{ liquid fuel costs})\ (92.8\ \frac{D_{pt}}{\Omega\text{-cm}})/100 +$$
$$(\Sigma \text{ construction contract design \& inspection}) \times$$
$$(-2.8 + \frac{1.25\ \Sigma(\text{O\&M corrosion costs}}{\Sigma(\text{O\&M costs})})/100$$
$$+ \text{ Energy losses (steam \& gas \& air \& POL)}$$
$$+ \Sigma \text{ (maintenance \& repair contracts, corrosion-related).}$$

COST CALCULATIONS BY SYSTEM

This method calculates costs by applying the total system dimension against a corrosion cost per unit dimension, which is some function of the corrosion percentage. In general,

$$S_j = \frac{\$\ corr}{V} \times V_j \text{ and } \frac{\$\ corr}{V} = f\ (C_i) \text{ for } \begin{array}{l} i = 1\text{-}11 \\ j = 1\text{-}8 \end{array}$$

where S_j = system corrosion cost

$\frac{\$\ corr}{V}$ = corrosion cost/unit dimension or capacity

V_j = actual installation dimension or capacity

$C_i\%$ = work center corrosion percentage

$$S_{total} = \sum_{1}^{8} (S_1 + S_2 + S_3 \ldots S_8)$$

The complete system corrosion cost equation is as follows:

Σ (corrosion costs) =

(Σ KLF gas & water lines) (188.2 - 0.0267 [ohm-cm]) +

(Σ KLF steam & hot water lines) ($6383 + 0.113$ MBtu/$T_{mF} - 90.7\ T_{mF}$) +

(Σ tonnage, refrigeration, & air conditioning) ($-11.1 + 0.29\ H_{rel}$) +

(Σ KLF exterior electrical lines) ($-11.4 + 0.976\ [0.6\ D_{pt}$

$+ 10 \log \Sigma SO_x]$) +

(Σ KSF total bldg surface) ($1.38 \sqrt{-54.7 + 0.835\ H_{rel}}$

$-28.3 + 0.483\ [R + T_{m°F}] - 4.0 + 0.108\ [D_{pt} + \Sigma SO_x] +$

$1.0 + 0.0975\ [D_{pt} + 10 \log \Sigma SO_x]$) +

(Σ KGAL water produced) ($-.187 + 0.00309\ H_{rel}$) +

(Σ maint & rpr contracts, incl planning, design & insp) ($0.014\ C_{O\&M}$) +

Σ corrosion-related energy losses (steam & gas & air & POL).

where

	H_{rel}	= relative humidity
	D_{pt}	= dew point, °F
	R	= mean annual rainfall, inches
	$T_{m°F}$	= mean ambient temperature, °F
	ΣSO_x	= cumulative sulfur oxide emissions, tons/yr/km^2
	$C_{O\&M}$	= composite O&M corrosion percentage
	POL	= petroleum, oil, and lubricants.

VERIFICATION OF WORK CENTER METHOD ACCURACY

Although the system model equation is more general, the work center corrosion-cost equation is more accurate since only one correlation is employed and costs are actual. Table 11 compares actual corrosion percentages with calculated percentages, along with real and calculated corrosion costs. In Table 12, these calculated costs derived from predictor work elements are summed up, resulting in a total corrosion cost. This calculated total cost is compared with actual costs by rating the percent deviation for all installations surveyed.

TABLE 11. CALCULATED VERSUS PREDICTED CORROSION COSTS

AF Work Center/ Army Section Equivalent	Actual Corrosion %	Predicted Corrosion %	Actual Corrosion Cost	Prediction Corrosion Cost
Plumbing	17.6[1]	17.1	48,061	46,695
	42.9[2]	43.3	81,247	82,005
	26.3[3]	39.5	99,481	149,410
	5.8[4]	6.2	15,976	17,078
	72.1[5]	34.3	201,543	95,879
	50.0[6]	53.7[a]	171,245	183,917
	40.0[7]	42.3	169,579	179,330
Heating Systems/ Boiler Plant; Heating Systems	29.0[1]	34.6	333,869	398,340
	11.2[2]	7.4	44,439	29,361
	39.2[3]	34.3	405,871	355,137
	41.0[4]	33.5	545,287	445,540
	20.9[5]	28.7	77,012	98,972
	8.4[7]	11.4	4,678	6,349
Refrigeration & Air Conditioning	13.8[1]	13.2	55,392	52,984
	14.2[2]	14.2	82,959	81,807
	12.6[3]	11.6	156,543	144,119
	24.0[4]	13.0	82,369	44,617
	10.0[5]	11.7	12,368	14,481
	19.0[6]	19.2	169,850	171,638
	7.9[7]	14.7	21,889	40,730
Power Production (No comparable Army section)	16.7[2]	not correlated	149,447	149,878[b]
	16.9[3]	not correlated	18,443	56,410[b]
	5.2[4]	not correlated	6,390	6,712[b]
Exterior Electric	1.0[1]	8.2	1,154	9,462
	19.3[2]	25.5	26,287	34,732
	9.0[3]	7.4	16,887	13,885
	0.1[4]	3.3	395	13,038
	17.2[5]	16.0	16,785	15,614
	24.0[6]	19.6	68,071	55,591
	24.0[7]	18.1	25,791	19,471
Interior Electric	1.0[1]	5.3	4,284	22,709
	5.1[2]	8.6	19,028	32,086
	2.2[3]	0.2	21.476	1,952
	2.7[4]	4.6	15,114	25,149
	2.9[5]	0.2	4,724	326
	26.0[6]	25.5	116,662	114,419
	15.0[7]	10.4	37,565	26,045

TABLE 11. CALCULATED VERSUS PREDICTED CORROSION COSTS (CONCLUDED)

AF Work Center/ Army Section Equivalent	Actual Corrosion %	Predicted Corrosion %	Actual Corrosion Cost	Prediction Corrosion Cost
Structures Maintenance	3.2[1]	3.5	20,298	22,521
Masonry/	33.8[2]	23.0	163,525	111,337
Carpentry	6.1[3]	5.9	29,414	28,338
	1.8[4]	1.2	14,781	9,854
	1.9[5]	0.5	6,289	1,655
	55.0[6]	54.5	382,634	379,154
	5.0[7]	19.4	18,552	71,982
Protective Coatings/	1.5[1]	2.7	3,989	7,180
Painting	17.6[2]	16.3	28,296	26,206
	5.3[3]	3.5	16,712	11,036
	1.2[4]	0.9	7,060	5,295
	10.5[5]	12.2	7,512	8,728
	7.5[7]	8.2	7,400	8,091
Metalworking	5.6[1]	10.8	12,825	24,734
	22.1[2]	18.5	33,847	28,333
	15.4[3]	11.8	84,194	64,512
	10.2[4]	9.7	26,503	28,696
	16.0[5]	13.8	12,448	10,736
	15.0[6]	17.7	33,328	39,327
	12.5[7]	14.1	25,281	28,517
Water & Waste/	5.8[1]	6.6	20,155	22,935
Water Plant;	5.8[2]	9.0	12,963	20,115
Sewage Plant	3.6[3]	2.8	20,754	16,142
	5.8[4]	6.1	7,740	8,140
	3.3[5]	2.8	3,176	2,695
	14.0[7]	10.4	55,105	49,935
Liquid Fuels/	1.0[1]	1.3	174	226
Fuel Storage and	53.0[2]	52.9	63,906	63,786
Issue (only AF data	8.6[3]	8.1	11,376	10,715
reported here)	30.0[4]	0.8	26,429	705
Programs; Engineering	12.7[1]	10.6	58,246	53,049
& Construction, Eng-Tech	18.1[2]	16.5	94,686	94,431
& Services; Construc-	15.3[3]	12.7	147,748	138,034
tion Management/	8.8[4]	10.2	58,220	73,363
Engineering Plans &	15.6[5]	17.5	37,606	42,187
Real Property[c]	37.0[6]	36.3	285,270	279,873
	9.7[7]	16.7	26,724	46,009

[a]Calculated from cost/KLF as a function of C_{pl} since soil resistivity data are not available.

[b]Calculated on basis of corrosion cost/KW - 36.3 + 1.1 [D_{pt}].

[c]Accounts for the contract design and management of corrosion-related construction projects; does not account for actual value of contracts.

[1]Chanute; [2]MacDill; [3]Tinker; [4]Griffiss; [5]Sheridan; [6]Amador; [7]Polk.

TABLE 12. ACCURACY OF WORK CENTER CORROSION COST MODEL[a]

Installation & Service	Actual Corrosion Cost, Incl[b] Labor, Materials & Equipment, $	Predicted Corrosion Cost, $	% Inaccuracy
Chanute (AF)	581,794	660,835	+ 13.6
MacDill (AF)	836,189	798,847	- 4.5
Tinker (AF)	1,048,073	989,690	- 5.6
Griffiss (AF)	837,180	678,187	- 17.5[c]
Sheridan (Army)	462,231	322,421	- 30.2[d]
Amador (Army)	1,346,390	1,223,921	- 9.1
Polk (Army)	519,296	476,459	- 8.2
		Arithmetic Mean = -8.8% Standard Deviation = +16.6%	

[a]Includes all direct maintenance costs and cost of design and inspection of corrosion-related construction projects. Value of construction contracts not included.

[b]Includes non-correlating work centers not accounted for in the model. Dollars are as actually reported and are not adjusted for inflation.

[c]Severe inaccuracy caused by deterioration of steam lines from deicing salts. Since heating expenditures are so large, the accuracies obtained in other correlations are distorted. Average base soil resistivity could not take this into account.

[d]A similar case where no cathodic protection has been applied on water and gas lines, coupled with advanced burial times (some as long as 70 years), has caused expenditures in plumbing systems to be inordinately high.

An examination of these results reveals that variation of the predicted versus actual corrosion percentage is not as critical as what the corrosion percentage is applied against. If the work center is very large, any inherent inaccuracy will distort those accuracies obtained in predicting corrosion costs of smaller work centers. This is especially the case for plumbing and heating systems, usually the largest corrosion-cost work centers.

When all the individual costs are combined for each installation, the aggregate percent inaccuracy averages about -8.8 percent.

PREDICTION OF CORROSION COSTS BY CLASSIFICATION

Not only may costs be predicted when certain climatic, topographic, or system dimensions data are known, but relative percentages of costs by classification were found to correlate with certain predictor elements. Using the classifications of (1) atmospheric corrosion, (2) high temperature oxidation, boilers and condensate, (3) refrigeration and air conditioning, (4) potable waters, and (5) underground corrosion, the respective relative percentages of total corrosion-related expenditures were correlated with logical predictor variables, such as dew point, mean temperature, water conductance, and soil resistivity. Those variables having the best correlation and minimal scatter were chosen.

The percent of overall corrosion effort directed toward limiting effects of atmospheric corrosion was best predicted by the dew point. The high correlation of 0.956 r-coefficient is remarkable. A high degree of correlation with dew point is found even if percentage atmospheric corrosion of all in-house O&M corrosion costs or contracted corrosion-related expenditures are broken down separately. Figure 24 shows this correlation, with this resulting predictor equation:

$$\text{Percent Atmospheric Corrosion} \pm 6.7 = -48.8 + 1.67\ D_{pt}$$

Boiler corrosion, loss of condensate lines, and high temperature oxidation were prevalent in locations with low mean ambient temperatures. In locations where underground corrosion or substantial air pollution may be dominant, there is substantial scatter. The low ambient temperatures usually limit atmospheric corrosion since the air carries less moisture, and the need for air conditioning is also curtailed. Nevertheless, Figure 25 reveals a good correlation ($r = 0.938$), although scatter is in evidence. The prediction equation for percent high temperature oxidation, boilers and condensate (percent HTB) is:

$$\%\ \text{HTB} \pm 7.9 = 77.7 - 1.04T_{mF} + 0.00119\ \frac{\text{MBtu}}{T_{mF}}$$

The percent of refrigeration-related corrosion was correlated between total tonnage or total tonnage/°F, which have nearly identical correlations. Total tonnage had slightly less scatter, and involves only one variable. Tonnage better explains installations located in colder areas where air conditioning is used for cooling of electronic equipment or other industrial processes, which is not taken into account by temperature or relative humidity. Figure 26 correlates tonnage capacity with percent refrigeration corrosion, and is predicted by the following equation:

$$\text{Percent Refrigeration Corrosion} \pm 3.5 = 2.5 + 0.000917\ X_{tons}$$

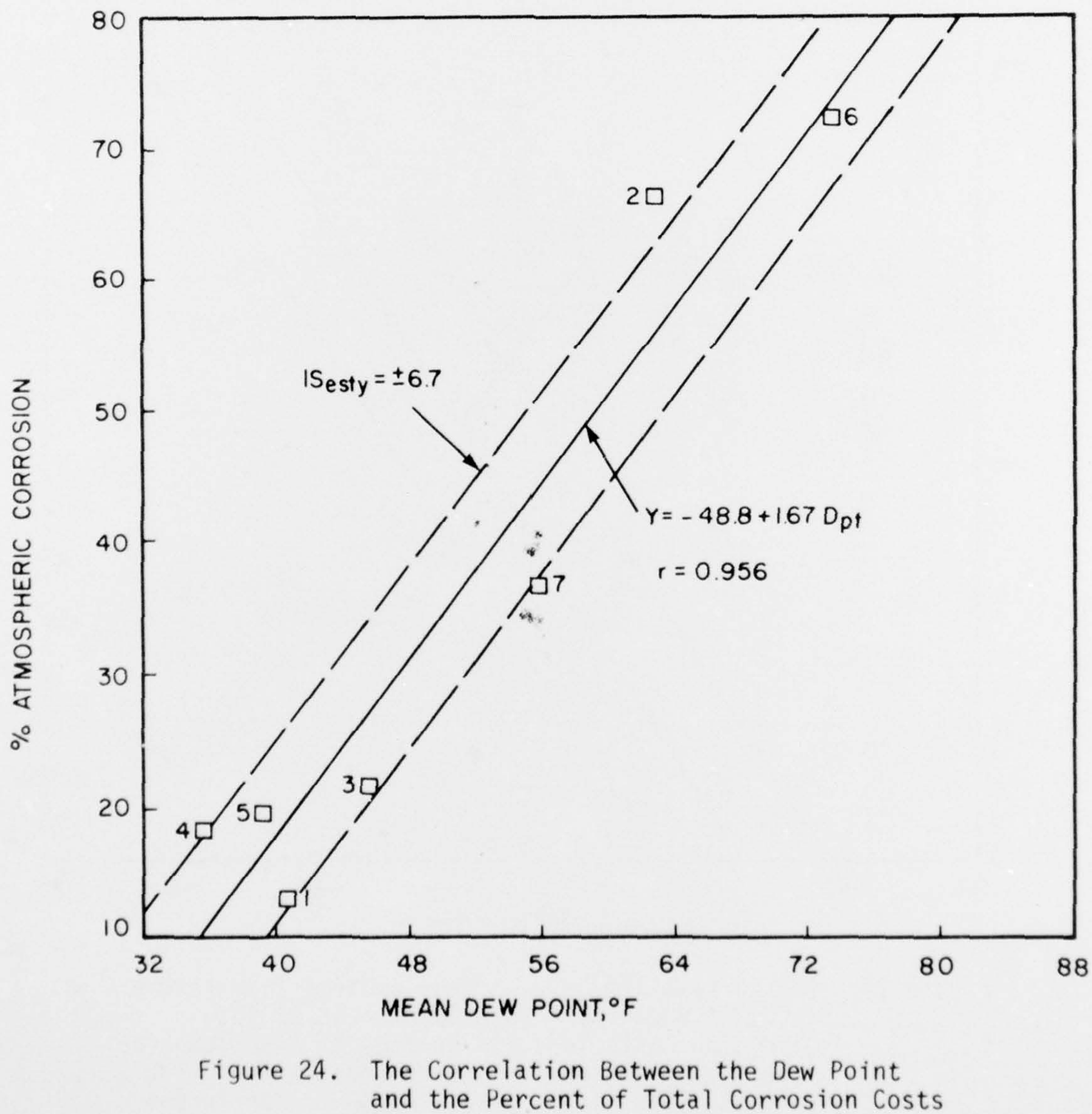

Figure 24. The Correlation Between the Dew Point and the Percent of Total Corrosion Costs Classified as Atmospheric Corrosion.

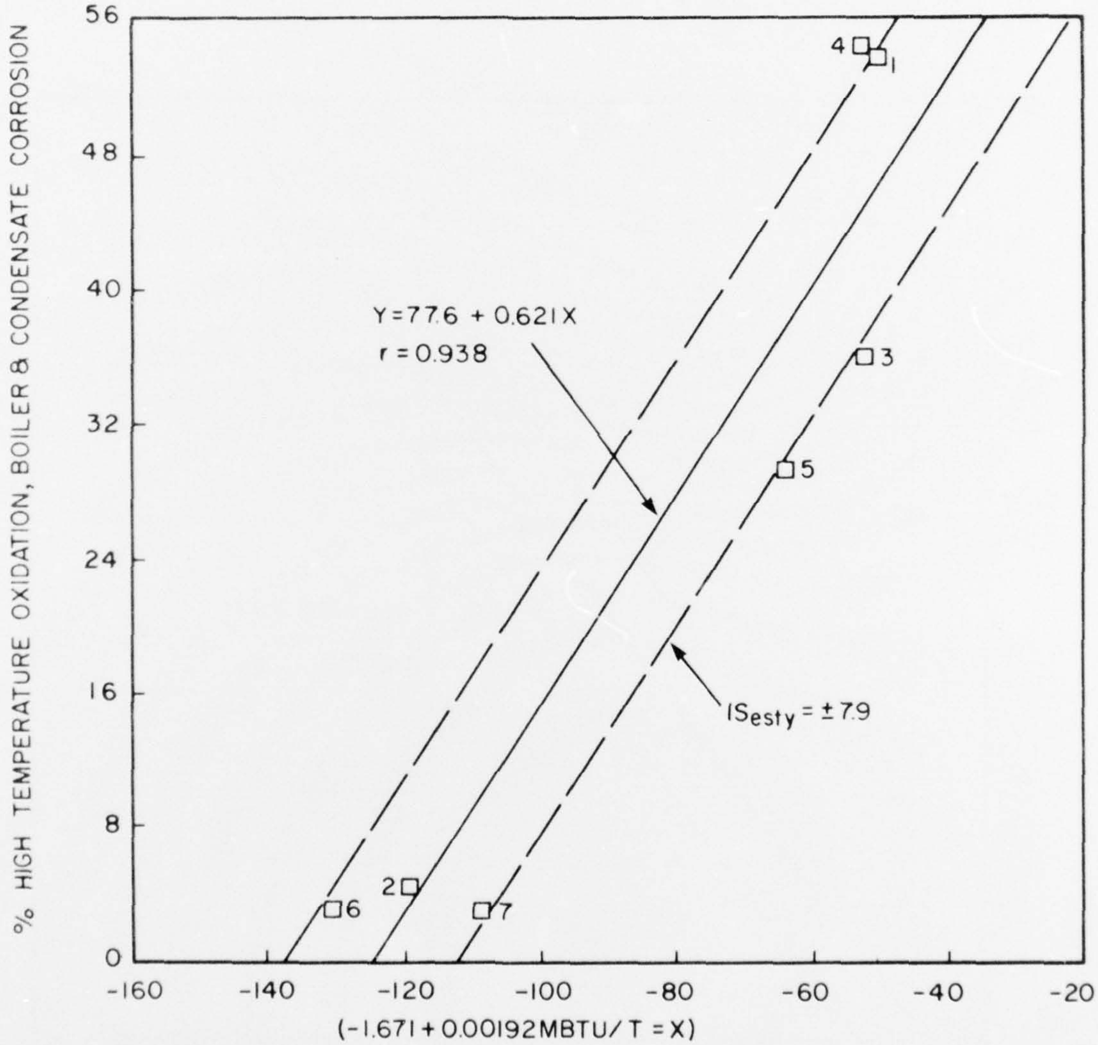

Figure 25. The Correlation Between Mean Ambient Temperature + Boiler Capacity/T and the Percent of Total Corrosion Costs That Are Related to High Temperature Oxidation, Boiler and Condensate Corrosion Losses. (The Factor MBtu/T Accounts for Excess Capacity Not Used for Building Heating.)

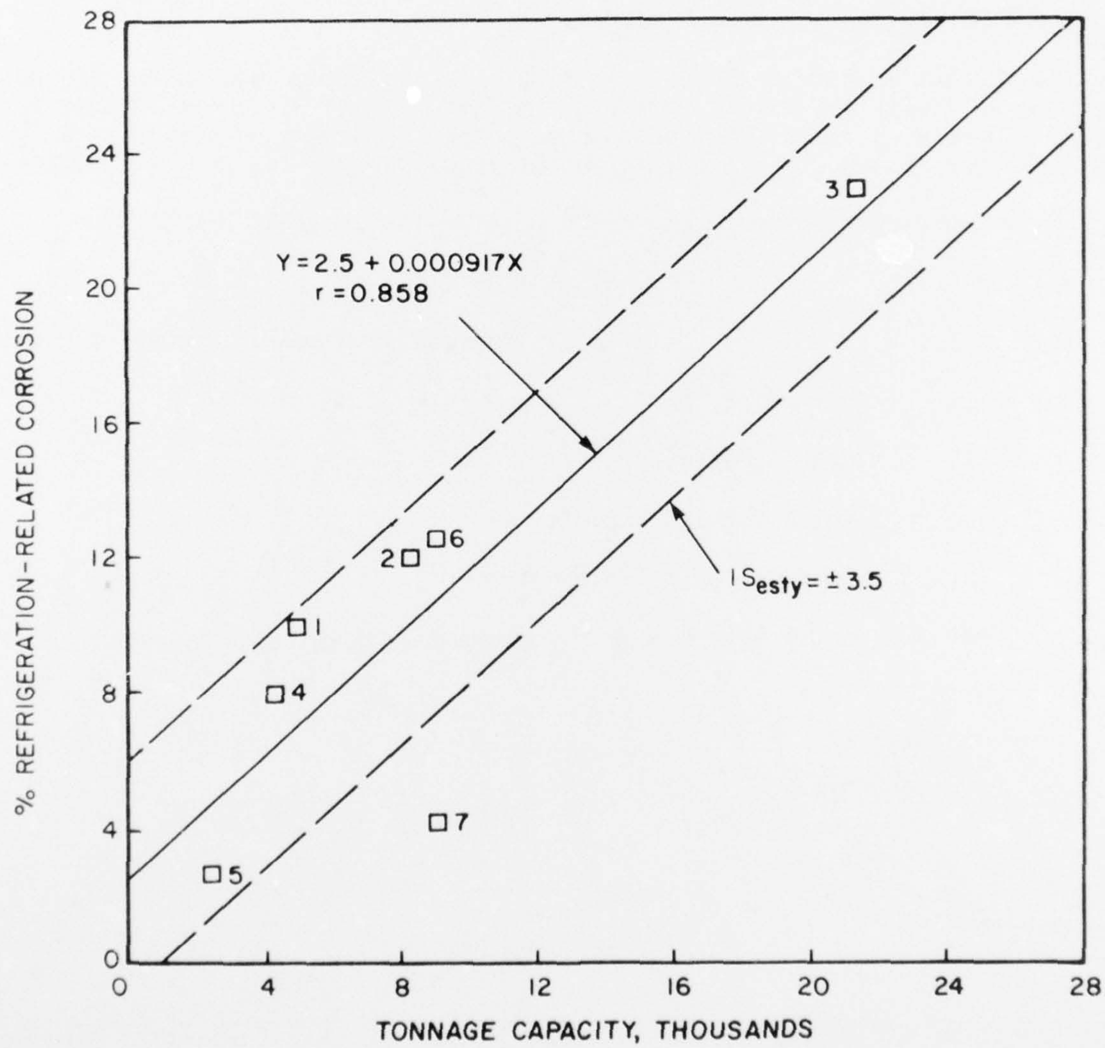

Figure 26. The Percent of Total Corrosion Costs That Are Refrigeration and Air Conditioning Related. Predicted From Total Installation Tonnage Capacity.

where X = total tonnage capacity.

Potable water is responsible for the corrosion of pipe interiors, valving, and water storage or disposal systems. The percent of this potable water corrosion control effort was correlated with conductivity, hardness, and total dissolved solids. The best predictor from a correlation standpoint appears to be calcium carbonate hardness, probably because excessive concentrations influence conductivity and contribute to flow blockage. See Figure 27 for this correlation. The prediction equation is as follows:

$$\% \text{ Potable Water Corrosion} \pm 1.6 = 3.3 + 0.0174\, H$$

where H = hardness, as $CaCO_3$, mg/l.

The percent of corrosion costs attributable to underground losses did not correlate well with any single variable, including high, low, or mean soil resistivity. Therefore, it was decided to make percent underground corrosion a function dependent on the other predictor elements by subtracting from 100 percent:

$$\text{Percent Underground Corrosion} = 100 - \%ATM - \%HTB - \%RFR - \%POT$$

or

$$= 100 - (34.7 + 1.67 D_{pt} - 1.04 T + 0.00119\ MBtu/T + 0.00917\ X + 0.0174\ H)$$

where D_{pt} = dew point, °F

T = mean temperature, °F

X = total tonnage capacity

H = hardness of potable water

$MBtu/T$ = total boiler capacity divided by mean temperature.

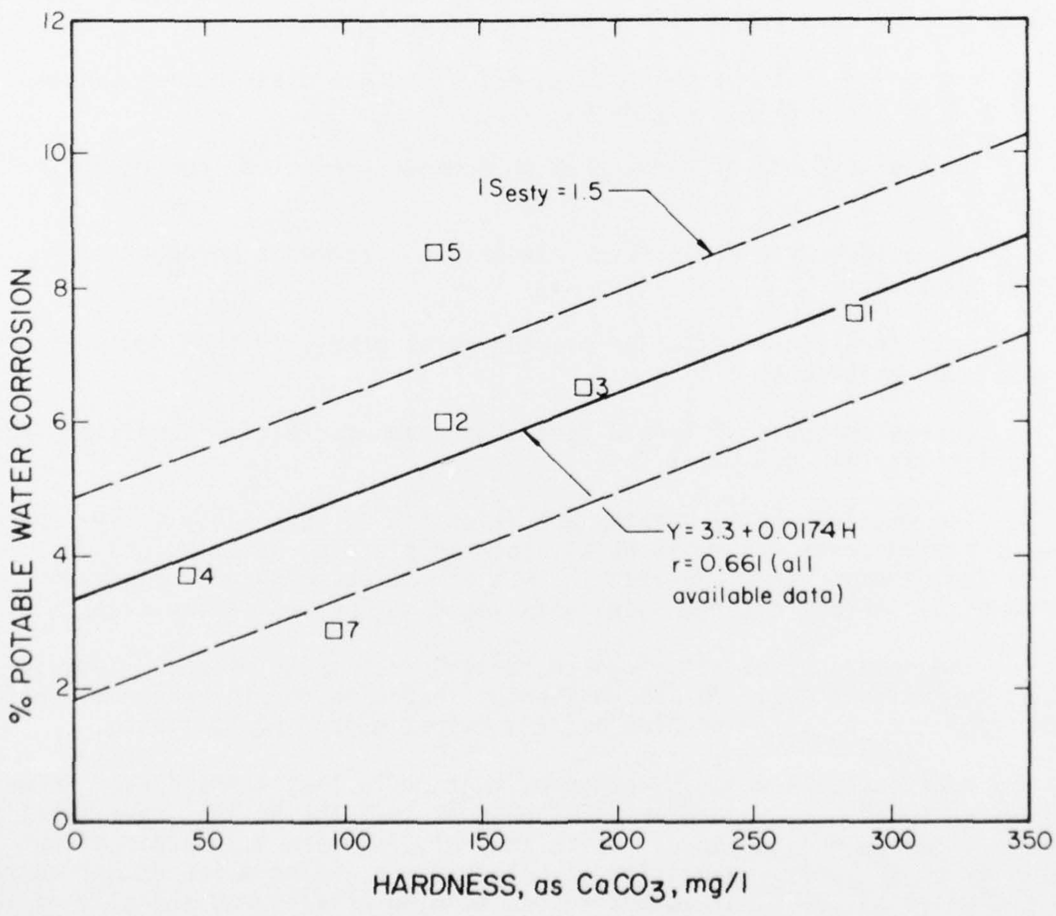

Figure 27. The Percent of Total Corrosion Expenditures Related to Potable Water Correlated With the Hardness of the Water, as $CaCO_3$, in mg/l.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

1. The validity of predicting corrosion costs from climatic, topographic, geographic, and environmental data obtained from conventional sources is established. Costs may be directly calculated from AF Civil Engineering work center costs or Army section costs, or they may be indirectly calculated with reasonable accuracy from facility system dimensions and capacities. Once overall costs are known, they may be sorted into various classifications by relative percent of the total.

2. Excellent correlations were obtained between the percent of effort expended on maintaining corroding systems and certain climatic, geographic, topographic, and environmental variables. Examples are:

a. Corrosion costs of maintaining water and gas distribution systems predicted from soil resistivity data;

b. Corrosion costs of refrigeration tonnage predicted from relative humidity;

c. Corrosion costs of interior electrical systems as a function of relative humidity;

d. Deterioration of exterior painted metal predicted from dew point and total SO_x emissions;

e. Corrosion costs of liquid fuel dispensing facilities predicted from soil resistivity and dew point.

3. The models require greater precision ($\pm 5\%$), especially in systems where corrosion costs are substantial, such as plumbing systems, heaters, boilers and refrigeration equipment. This can be accomplished by use of additional variables, although such data would not be ordinarily available.

4. The magnitude of actual corrosion costs at major military installations justifies a positive and continuous corrosion control program. Efforts emphasizing the corrosion problem and its extent should be continued.

5. Weaknesses in existing programs must be further identified. Known weaknesses include (a) inadequacies of present training or its unavailability to those directly engaged in corrosion control, (b) lapses in application of quality control, (c) repetition of prior design errors which do not decrease life cycle costs, (d) insufficient record keeping on failures and size of leaks, and (e) spotty cost accounting of corrosion-related expenditures to note whether attempted solutions were beneficial.

6. An improved method of delivering corrosion prevention technology to field personnel must be employed to reduce substantial losses. This can be modeled after the way new technology is delivered to combat forces, such as

through time-compliance technical orders (TCTOs) and formalized training packages for civilians. To increase awareness of the corrosion problem, a more simplified corrosion cost calculation procedure should be made available to base-level engineering personnel to rapidly identify corrosion problem areas for management.

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